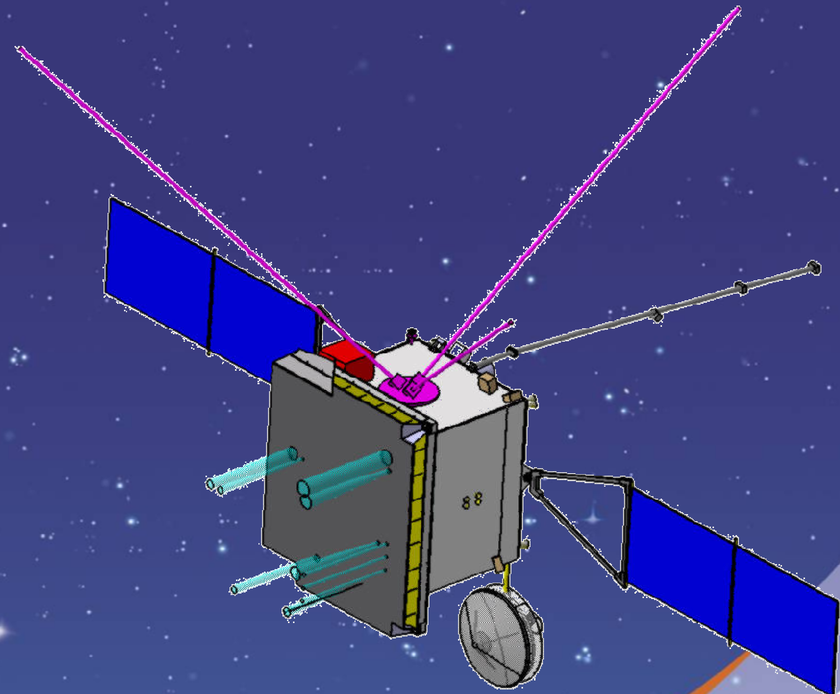
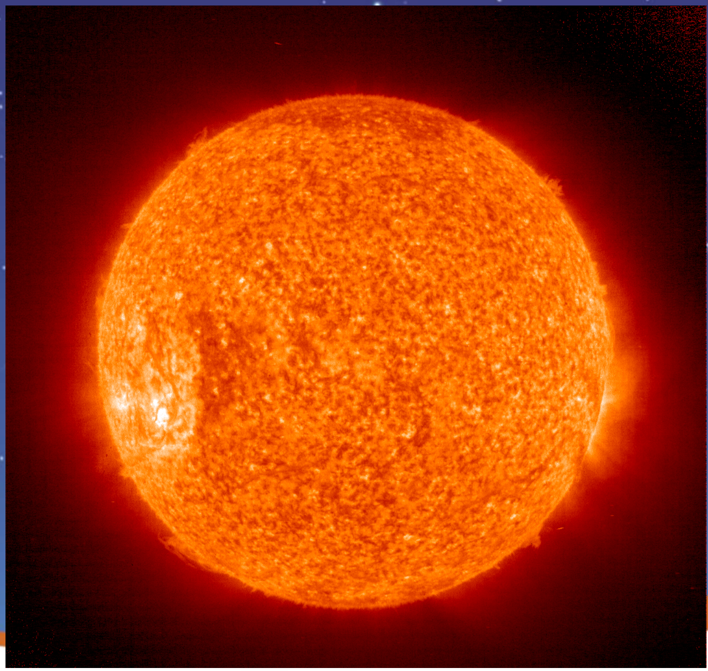
Solar Orbiter Heat Shield / System Technology study Final Review (FR)

ESTEC, October 2nd 2007





All the space you need

EADS astrium

Ref SOL-T-ASTR-PRS-74

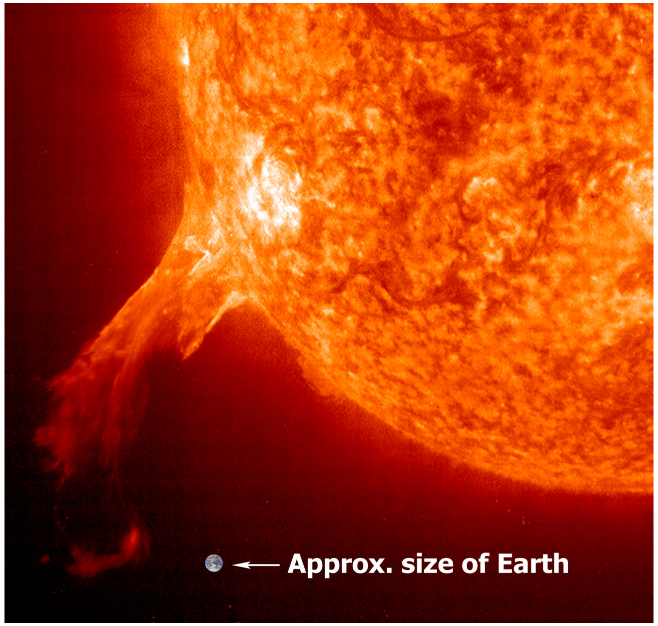
Agenda

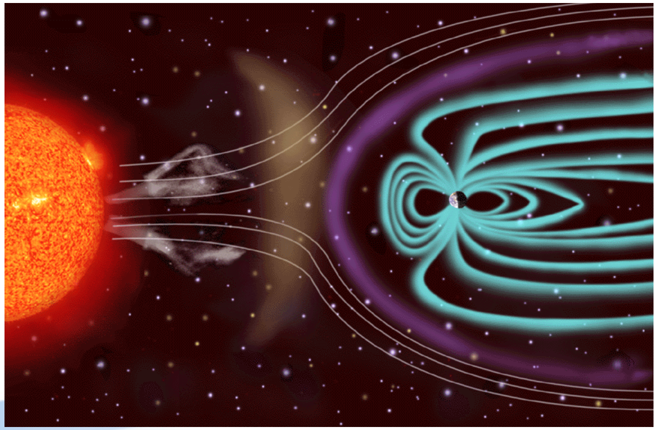
▪ **Introduction**	**9h30**
▪ **System and mission requirements**	
▪ Science objectives	
▪ Mission requirements	
▪ Mission analysis	
▪ **Payloads accommodation**	
▪ **Solar Orbiter System design**	**10h00**
▪ Configuration	
▪ Subsystems	
▪ Budgets	
▪ Enabling Technologies (HGA & SA)	
▪ **Coffee Break**	**10h45**
▪ **Heat Shield & breadboard**	**11h00**
▪ HS requirements	
▪ HS trades & optimisation	
▪ HS design & configuration	
▪ BB test program and tests results	
▪ HS thermal performance	
▪ **CCN1 on Atlas launch**	**11h45**
▪ **Synthesis and conclusions**	**12h00**

Introduction

Introduction

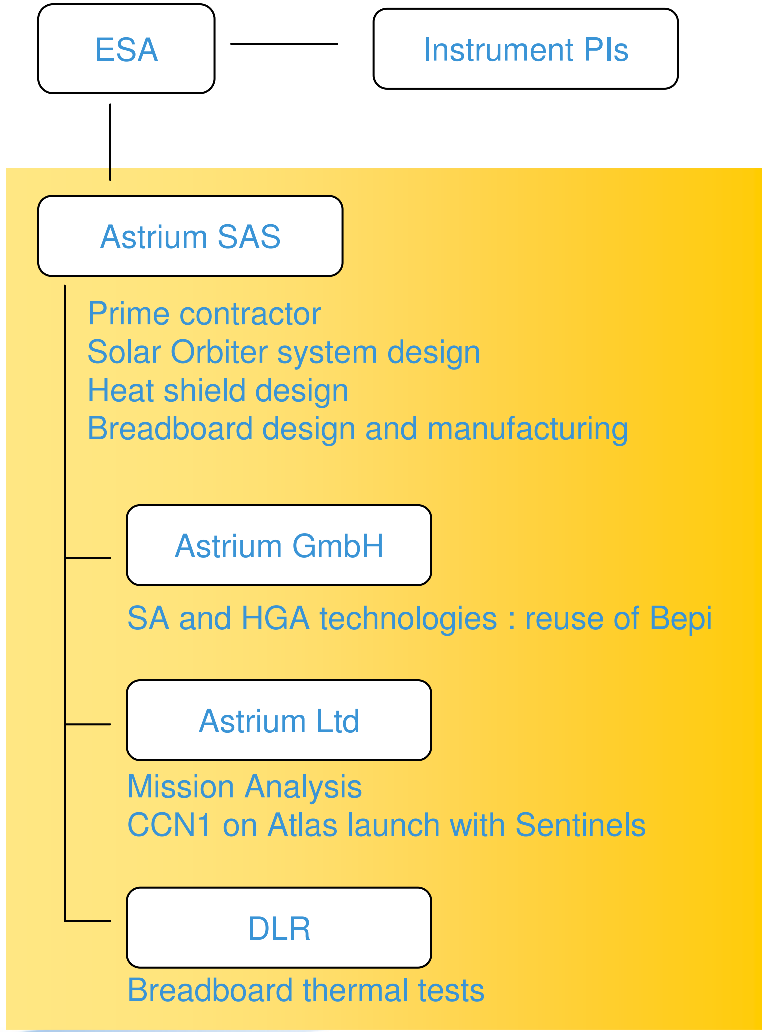
- The Solar Orbiter mission:
  - Candidate for the ESA Science Programme Cosmic Vision, as the next mission after BepiColombo;
  - Launch foreseen in 2015
- Heritage:
  - SoHO (ESA/NASA), launched in 1995 and still in function
  - Solar Orbiter Assessment studies & payload studies, Astrium, 2003 – 2005.
- On going:
  - Announcement of opportunity end 2007;
  - Oct 2006: Heat Shield / System Technology study, including a heat shield demonstrator test.





Heat shield/System technology study

- Objectives:
  - Evaluate new instruments inputs and propose EID-A updates.
  - Update instrument accommodation
  - Revise MRD, mission inputs, System design
  - Define proposals for Heat Shield design
  - Implement a breadboard test program
  - Review technology critical areas SA / HGA
- Milestones:
  - Kick-Off : November 1st 2006
  - Mid-Term Review : mid March 2007
  - Test Readiness Review : mid Aug 2007
  - Test Review Board : Sept 2007
- Organisation
  - Interface with PIs through ESA only
  - CCN1 on Atlas launch with Sentinels

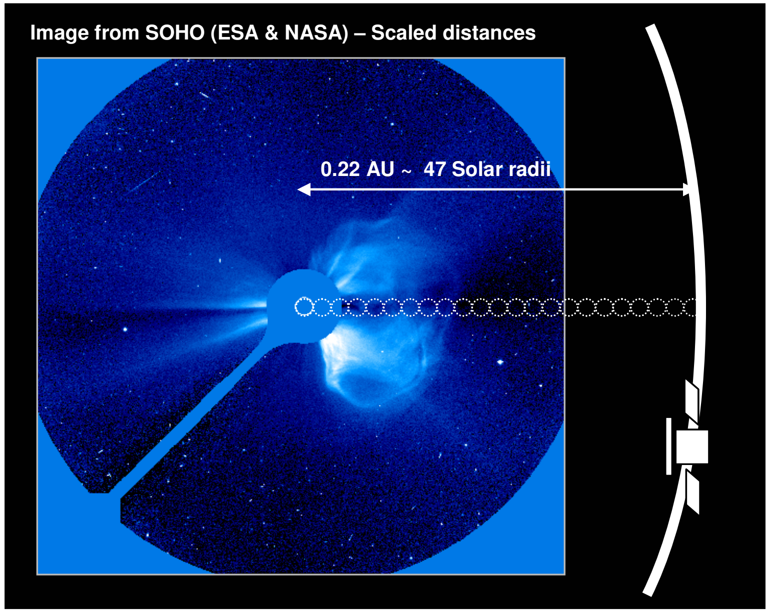


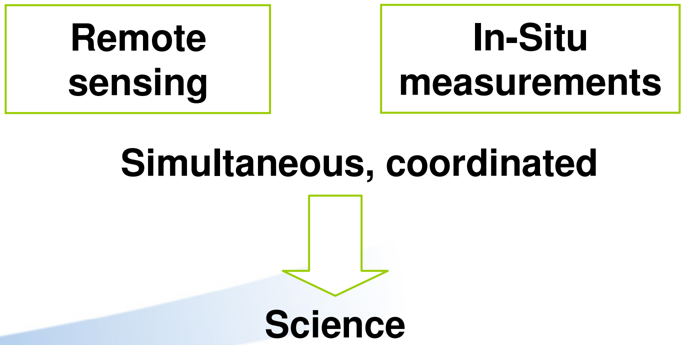
Mission and System requirements

Science objectives

- **Next step** in the Sun's observation from space:
  - Exploration of the uncharted innermost regions of the solar system;
  - Observation of the Sun from close-up (***down to 0.22 AU)***;
  - Sun observation from a quasi-co-rotating vantage point (spatial resolution 100km pixel size);
  - Heliographic latitudes in excess of 30 deg.

- **Science objectives**:
  - Determine the properties, dynamics and interactions of plasma, fields and particles in the near-Sun heliosphere;
  - Investigate the links between the solar surface, corona and inner heliosphere;
  - Explore, at all latitude, the energetics, dynamics and fine-scale structure of the Sun's magnetized atmosphere;
  - Probe the solar dynamo by observing the Sun's high latitude field, flow and seismic waves.





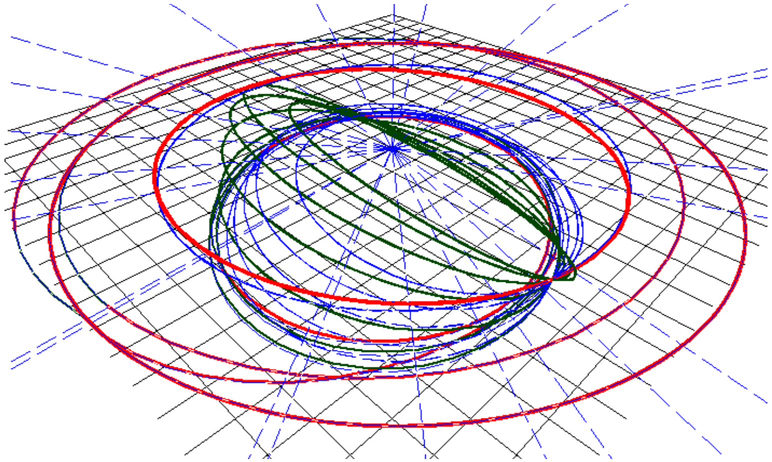
Mission drivers

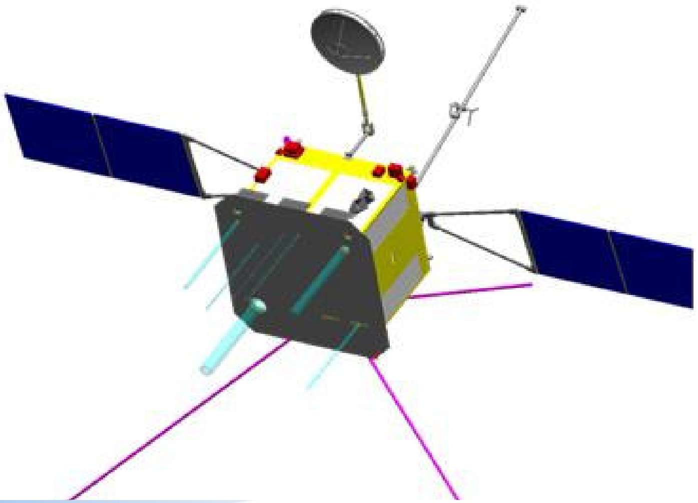
- Interplanetary Cruise
  - Long cruise duration (about 3.5 years),
  - Large & variable Earth distance (up to 2 AU),
  - Variable distance from the Sun (max 1.5AU).
- Very short distance to the Sun during operations
  - High solar thermal fluxes (~ 28500 W/m²).
  - High solar winds,
- Science measurements
  - A set of about 10 instruments,
  - Very high pointing accuracy and stability,
  - Stringent cleanliness levels,
  - Remote sensing instruments exposed to Solar heat flux through openings.

Orbit	Perihelion between 0.2 AU and 0.25 AU, for at least 3 consecutive orbits. Aphelion between 0.8 AU and 0.9 AU. Co-rotation pass: duration 10 days, with a maximum drift of 50°. Period about 150 days. Inclination evolving from 0° to 30°(with respect to solar equator), 34° in the extended mission.
Core Payload	Overall budget: 180 kg; 180 W; 90-100 kbps. Remote sensing instruments package: VIM, EUS, EUI, COR, STIX Heliospheric in-situ instruments package: SWA, RPW, MAG, EPD, NGD, DUD
Science phase	Nominal duration: 3 years; extended mission duration: 3 years more. Science data collection & storage around perihelion. Science data downlink to Earth when spacecraft is far enough from perihelion.
Cruise phase	Goal is less than 3 years, with valuable science doable during cruise.

Transfer strategy trade-off

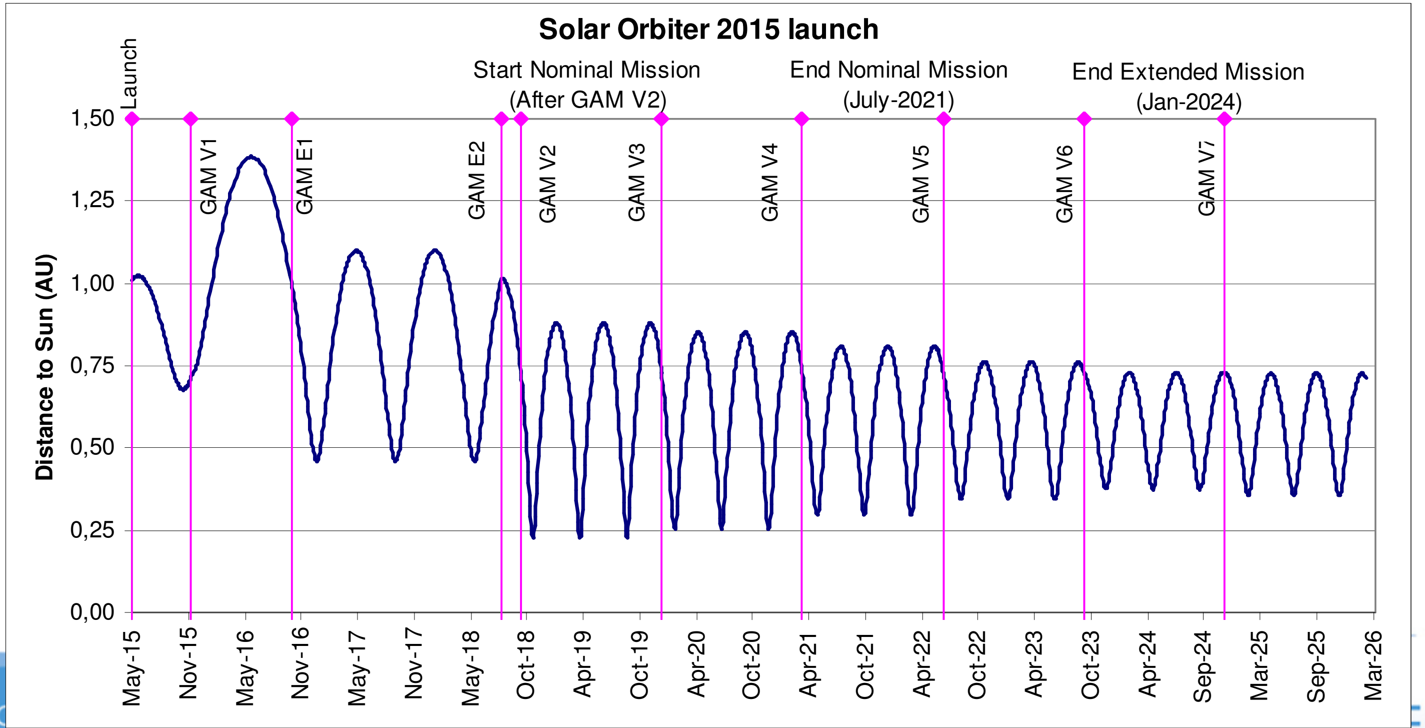
- High Sun latitudes at close distance calls for high energy transfers.
- → *Ballistic mission based on chemical propulsion as baseline*, owing to smaller cost and better mass margins, for a reasonable increase in the cruise phase duration.
- Successive Venus gravity assists to obtain the high inclinations (reaching more than 30 degrees during nominal science phase)



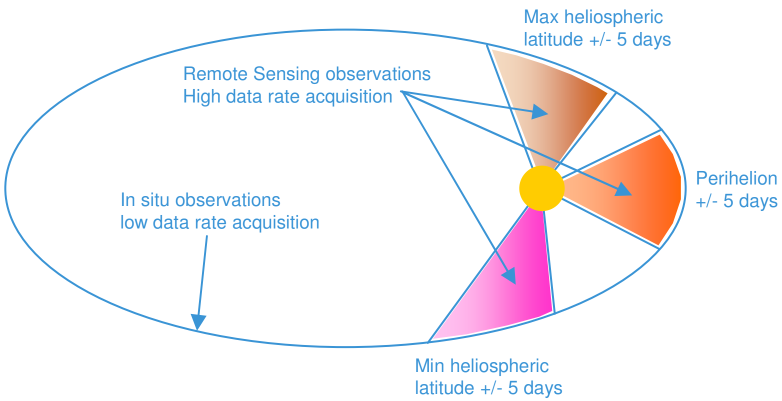


Mission analysis details

	2015 baseline	2015 variant	2017 back-up
Launch Date	22 May 2015	22 May 2015	9 Jan. 2017
Min. Sun distance	0.225 AU	0.219 AU	0.228 AU
Max. Sun distance	1.38 AU	1.38 AU	1.49 AU
science ops start (GAM2)	3.39 years	3.39 years	4.09 years
Solar equatorial Inclination & Science ops end	31.7° after 7.1 years	32.1° after 7.1 years	30.2° after 8.4 years
Deep Space Manoeuvre	45 m/s	212 m/s	0m/s
Duration to Final Inclination	33.9° after 8.3 years	34.6° after 8.3 years	34.3° after 9.63 years



Main system requirements



- Mission duration and phases :
  - 3.5 years cruise,
  - Nominal mission phase from VGAM4 to VGAM6,
  - extended mission from VGAM4 to VGAM6:
- Science windows
- Payloads : 180 kg, 180 W, 90-100 kbps
- Communication : 200 kbps at 1 AU, permanent communication with New Norcia except planetary alignments outages
- Pointing performance

Requirement	Pointing Parameter	Line of Sight (X_{Op})	Around Line of Sight
POIN30a	APE : Absolute Pointing Error	< 2 arcmin	< 20 arcmin
POIN30b	PDE : Pointing Drift Error	< 1 arcmin / 10 days	< 10 arcmin / 10 days
POIN30c	RPE : Relative Pointing Error	< 1 arcsec / 10 secs	< 2 arcsec / 10 secs
POIN30d	AME : Absolute Measurement Error	No req (TBC)	< 3 arcmin in 10 secs

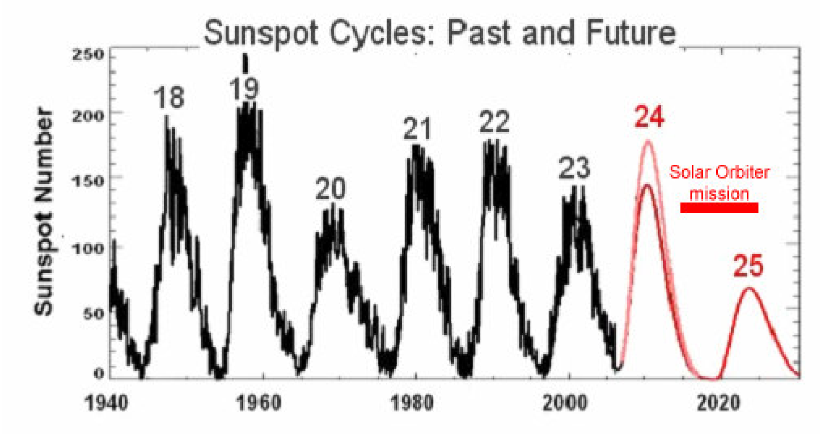
- System margins

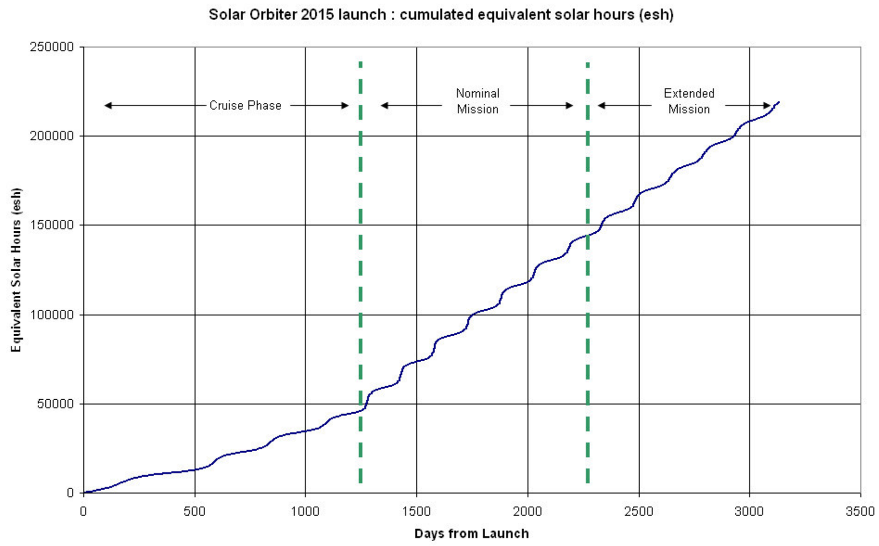
Applicable to:	*ECSS Category*	*MRD V3.0 (MASS25)*
Off-the shelf items with no modifications	*A/B*	***7 %***
Off-the shelf items with minor modifications	*C*	***> 10 %***
New design items, or items with major re-design	*D*	***25 %***

- Heat shield shall be testable a sub-system level prior integration

Mission Environment

- Launch baseline in May 2015:
  - Mission starts during solar min. activity period,
  - ends with the 25th solar cycle max. activity.
- Solar electromagnetic flux:
  - Average: factor 4 greater than an Earth mission,
  - Peak : 20 SC = twice as hard as BepiColombo.
- Plasma (Solar Wind) environment is also expected to be severe.
- High concentration of solar wind particles, high UV-flux and high temperature of exposed areas will deserve geart care for the external coating of the spacecraft sun shield.





Payloads

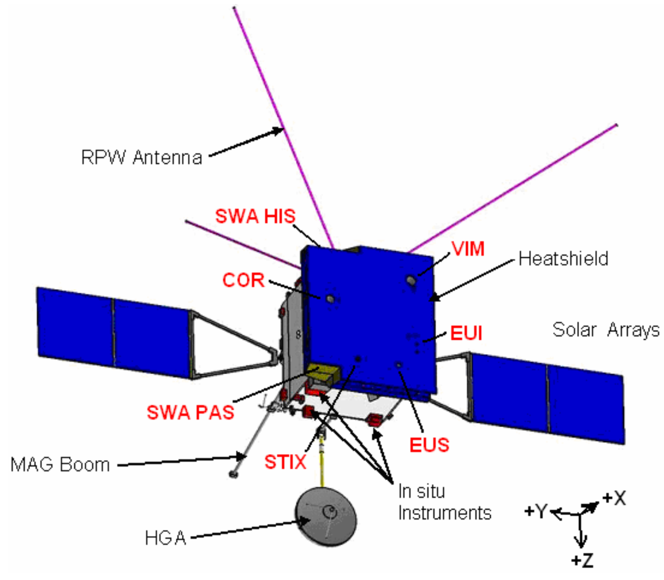
Science Payloads: generic instruments

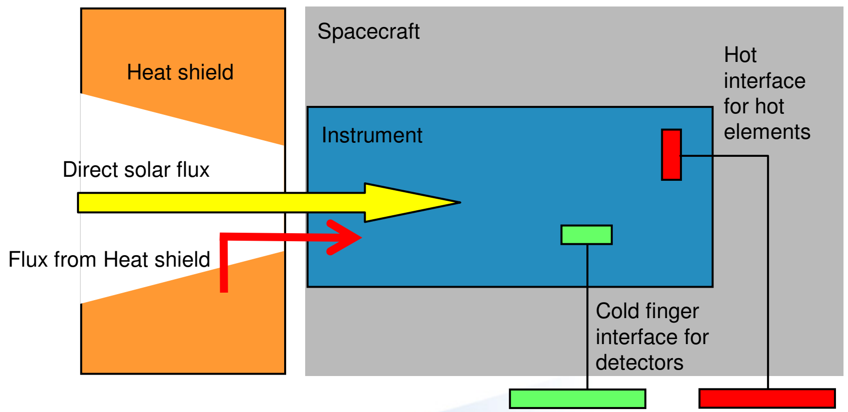
Remote-Sensing Instruments			Mass (kg)	Power (W)	TM (kbps)
VIM	Visible Imager & Magnetograph	Investigation of the magnetic and velocity fields in the photosphere	30,4	35,0	20,0
EUS	EUV Spectrometer	Investigation of properties of the solar atmosphere	18,0	35,0	17,0
EUI	EUV Imager	Investigation of the solar atmosphere using high resolution imaging in the EUV	20,4	28,0	20,0
COR	Visible Coronograph	Investigation of coronal structures using polarized brightness measurements in Visible	18,3	30,0	10,0
STIX	Spectrometer Telescope Imaging X-Ray	Investigation of energetic electrons near the Sun, and Solar X-ray emission	4,4	4,0	0,2
PSE	Payload Support Elements	Boom, VIM filter, EUS filter (TBC), instrument doors, thermal interfaces	26,0	4,0	
In-Situ Instruments					
SWA	Solar Wind Plasma Analyser	Investigation of kinetic properties and composition (mass and charge states) of solar wind plasma	16,5	15,5	7,0
RPW	Radio and Plasma Wave Analyser	Investigation of Radio and Plasma waves including coronal and interplanetary emissions	13,0	7,0	5,0
MAG	Magnetometer	Investigation of the solar wind magnetic field	2,1	1,5	0,8
EPD	Energetic Particle Detector	Investigation of the origin, acceleration and propagation of solar energetics particles	15,1	14,5	3,1
DPD	Dust Particle Detector	Investigation of the flux, mass and major elemental composition of near-Sun dust	1,8	6,0	0,1
NGD	Neutron Gamma ray Detector	Investigation of the Characteristics of low-energy solar neutrons, and solar flare processes	5,5	5,5	0,4
			171,5	**186,0**	**83,6**

Source : ESA Payload Definition Document SCI-A/2004/175/AO v5.0 dated 31,03,2006

Remote sensing instruments

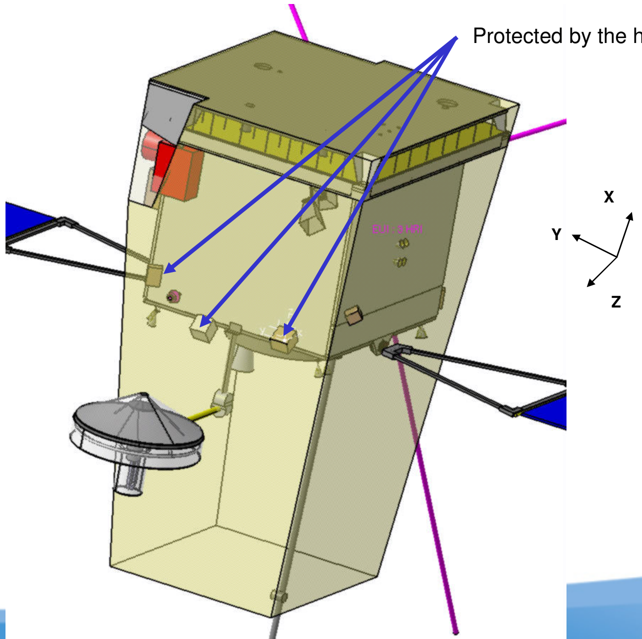
- Aperture through the heat shield is required.
- Accommodation either inside spacecraft, behind the heat shield, or outside the spacecraft, at heat shield corner
- A thermal baffle is inserted in the heat shield for each of the RS instruments
- Instruments thermal control through hot interface and cold interface at spacecraft level:
  - Each of the candidate for remote sensing observations has been analysed
  - Each candidate is a particular case
  - Accommodation feasibility: no real stopper with the available information

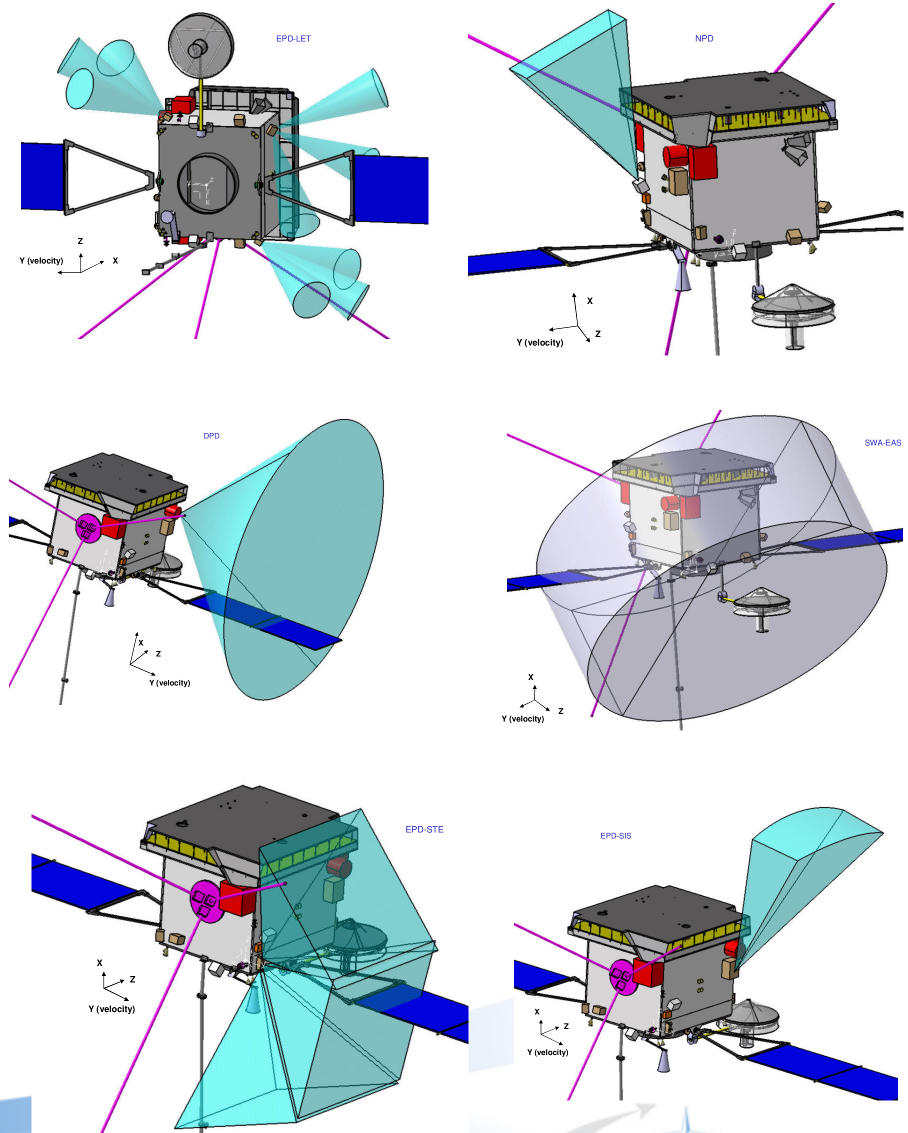




In-situ instruments

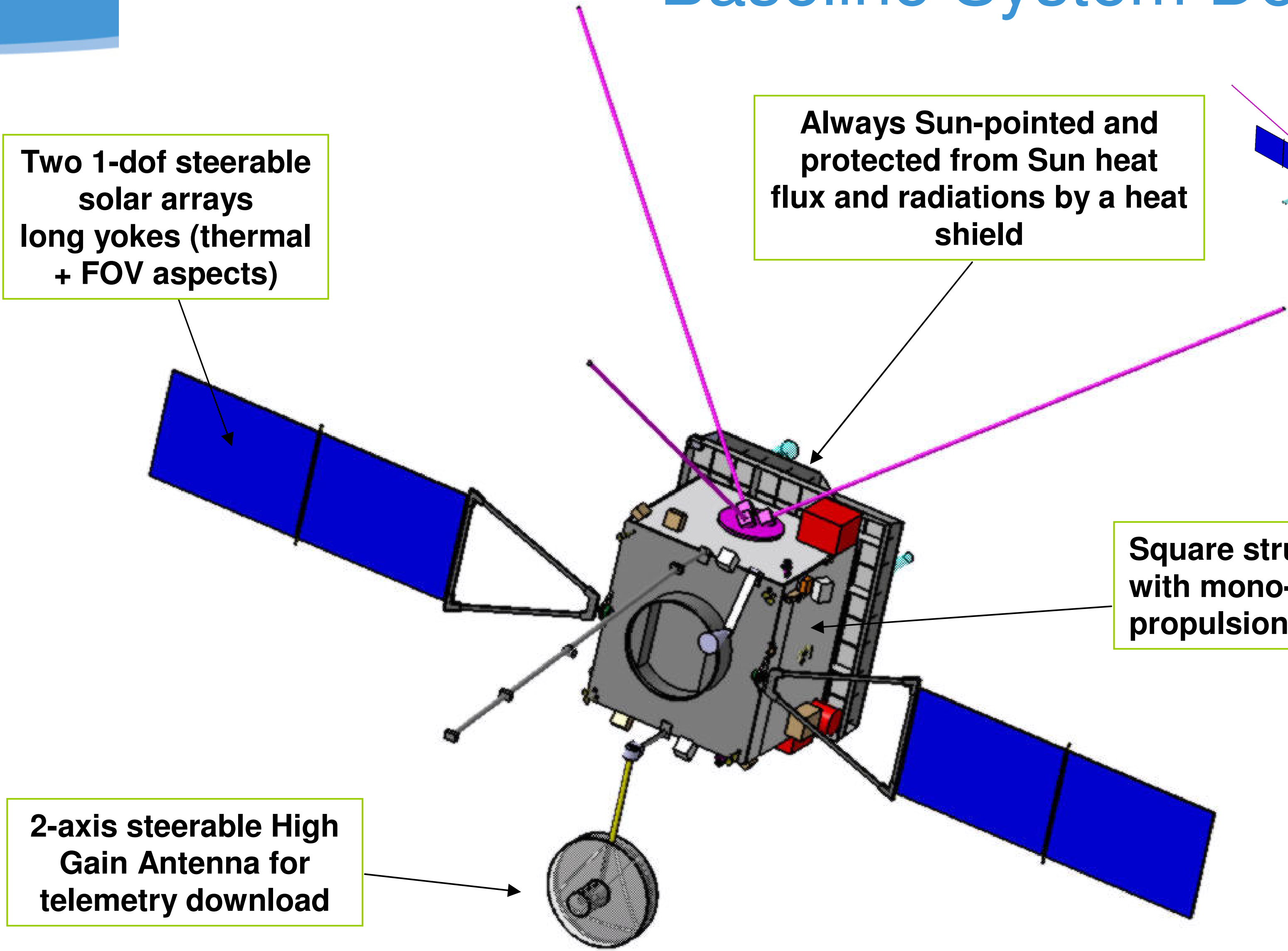
- Mounted on external walls, in the shadow of the heat shield.
- Instruments thermal control through dedicated radiator on each payload:
  - Each of the candidate for remote sensing observations has been analysed
  - Each candidate is a particular case
  - Accommodation feasibility: no real stopper with the available information

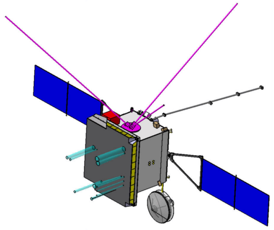




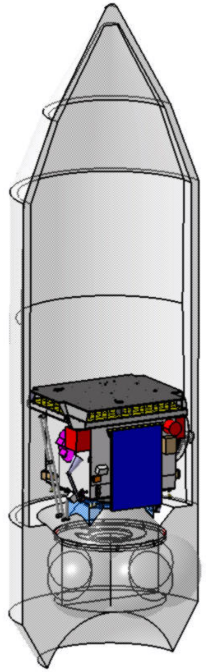
System design

Baseline System Design

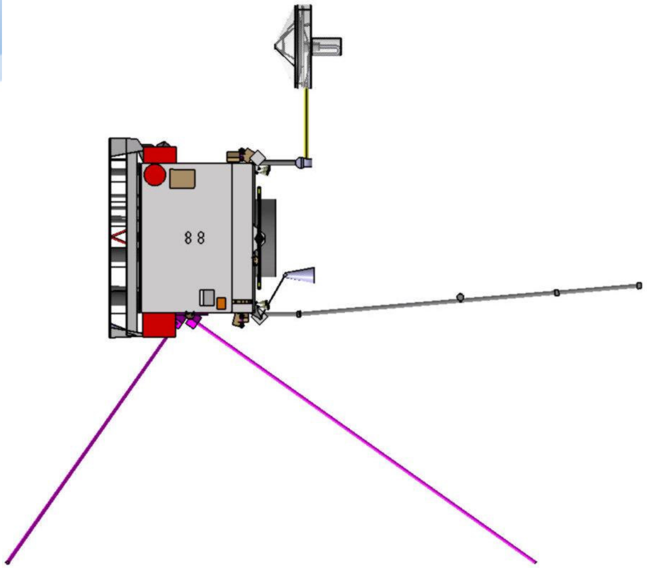




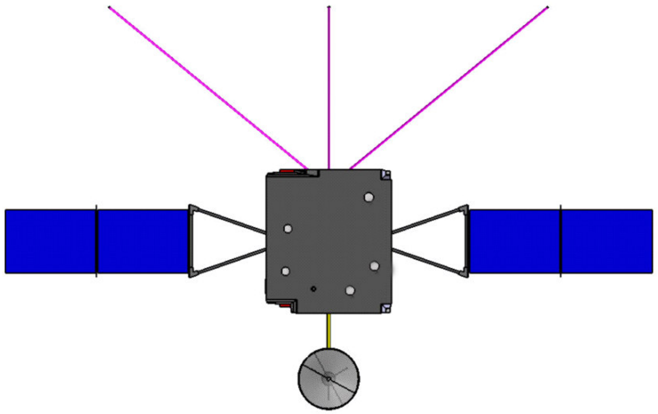
Configuration

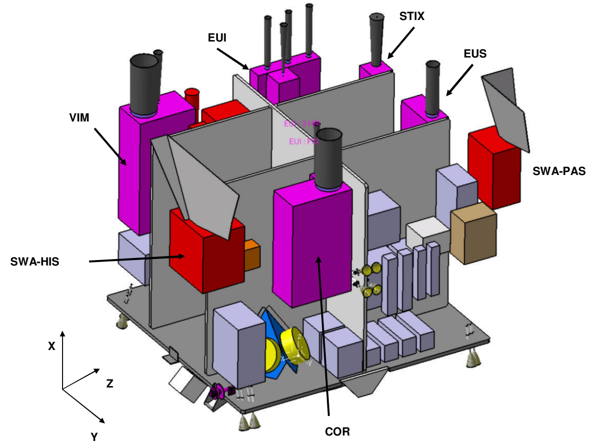


Stowed configuration under Soyuz-ST fairing

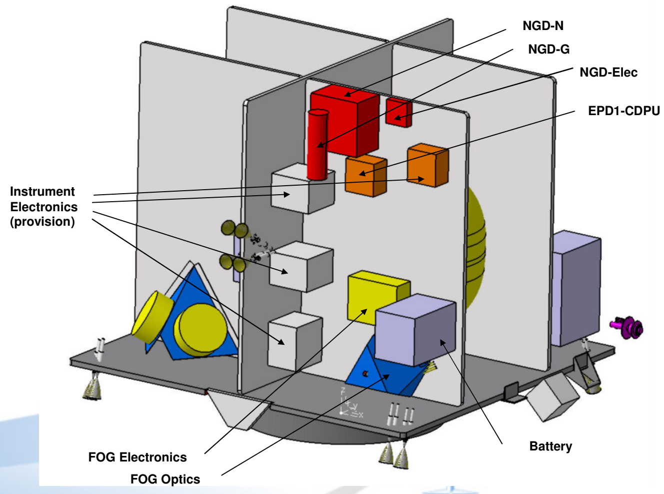


Flight configuration, with apertures in heat shield as a function of payload selection





Example of internal accommodation



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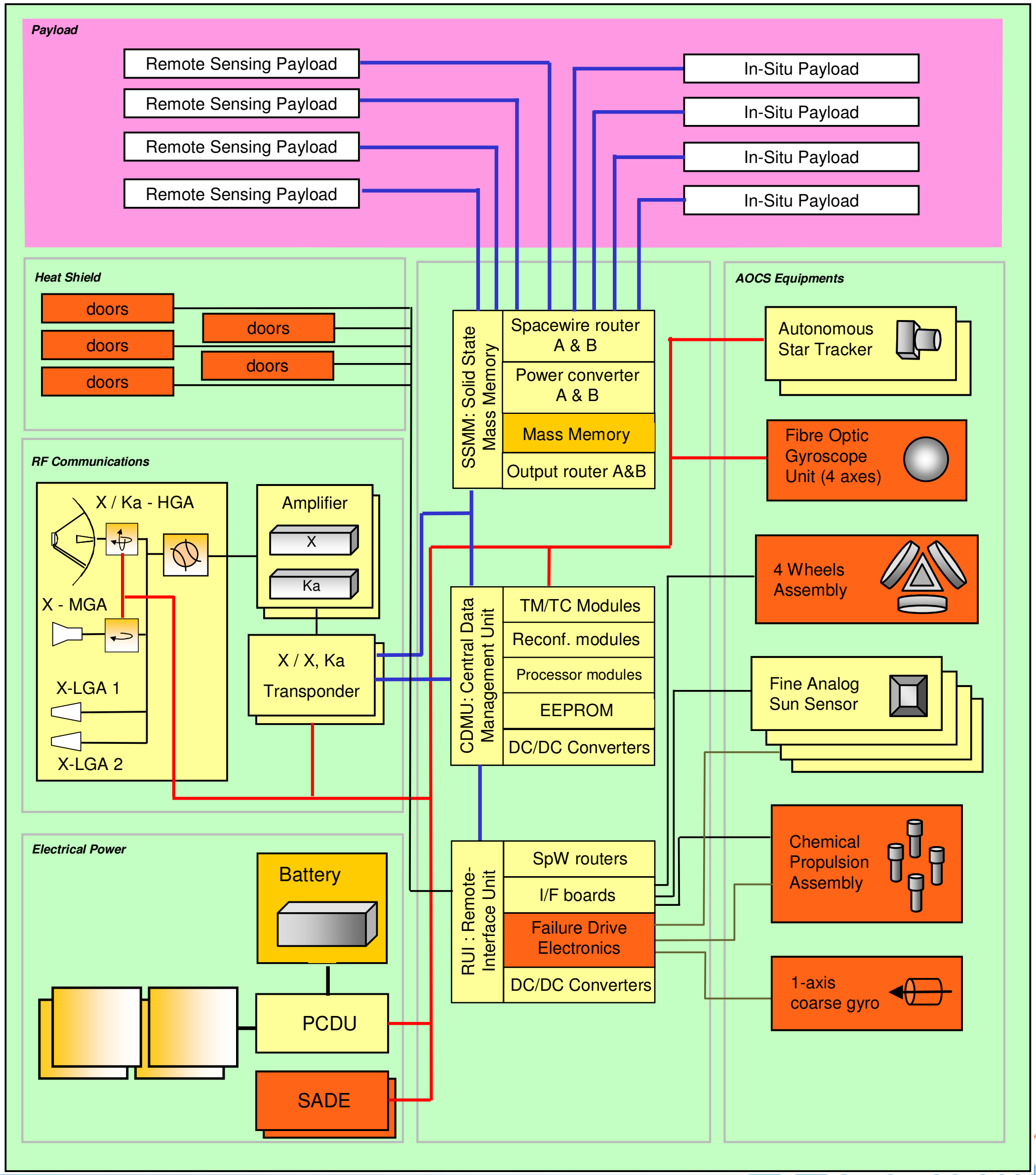
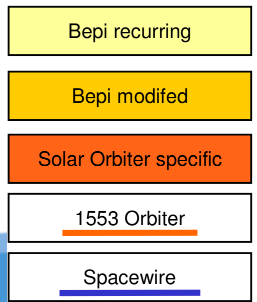
Functional architecture

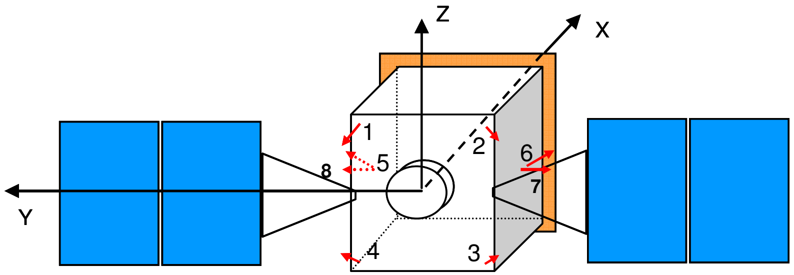
- Hard-wired safe mode to prevent from Sun off-pointing.
- High recurrence and synergy with Bepi-Colombo mission.
- One 2-axis HGA,
  one 1-axis MGA,
  two LGAs



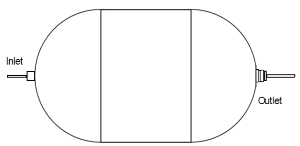


Propulsion subsystem

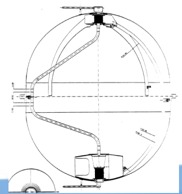
- Update of the hydrazine system sizing:
  - ΔV budget in the range of 320 m/s for the most demanding mission case
  - Tank capacity about 350 liters.
  - 175 litres per tank: Herschel-Planck tanks
- 8 thrusters for no off-pointing below 0.9-1 AU (impact of large radiators area on Y faces)
  - 5 N thrusters
  - Optimized efficiency with lateral thrusters mounted on lateral panels



Pressure Systems Inc



MAN Space Products



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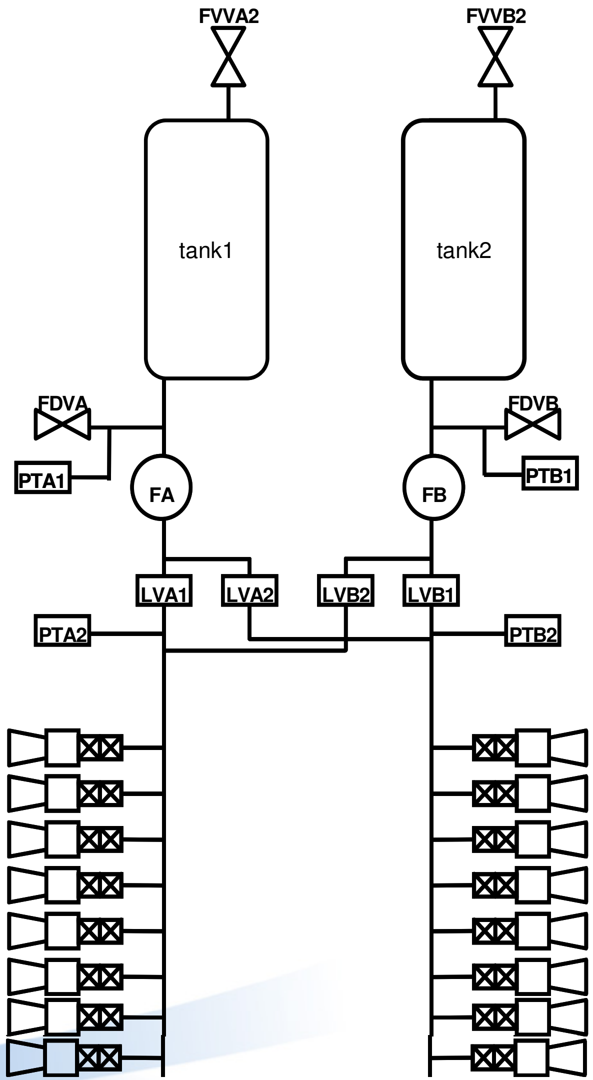
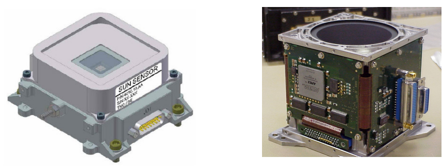


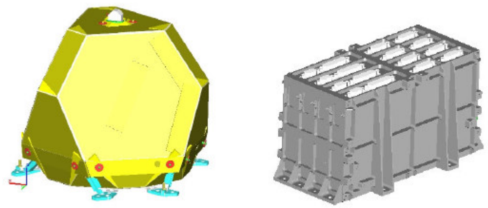
AOCS subsystem

- AOCS Interplanetary mission base on high heritage from Rosetta / Mex / Vex
- Highly accuracy is required for remote-sensing payloads.
- Attitude estimation based on
  - Gyro-stellar hybridisation
  - Sun sensors for attitude acquisition and safe modes
- Reaction wheels and thrusters for actuation
- Optimized pointing stability through:
  - Special measures at wheel management system (reduced speed, elastomers)
  - High performance gyros

	RRM	SAM	SHM	NM			HWSKM
				RWO	IPS	FSP	
Gyros	X	X	X	X	X	X	
Analog FSS		X				(X)	
STR			X	X	X	X	
RWs			X	X	X	X	
Thrusters	X	X	X	X			X
APME			X	X	X	X	
SADE		X	X	X	X		
Analog FSS (FDIR) + 1-axis coarse gyro							X



Bepi Colombo Sun sensors and Star tracker
(here examples with TNO SAS and Galileo STR)



High performance gyros : Astrix 200

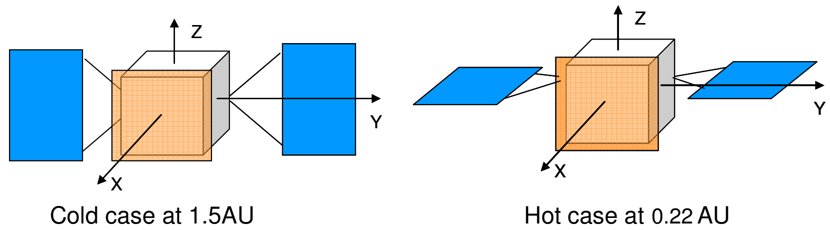
68 Nms Teldix Wheels

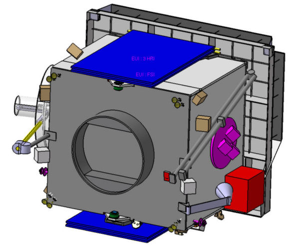
	RPE (arcsec over 10 s)
µmeteoroids	negligible
Solar pressure noise	negligible
Solar wind	negligible
Wheels µvibs	0.2-0.5
HGA pointing	0.4
AOCS control	0.25

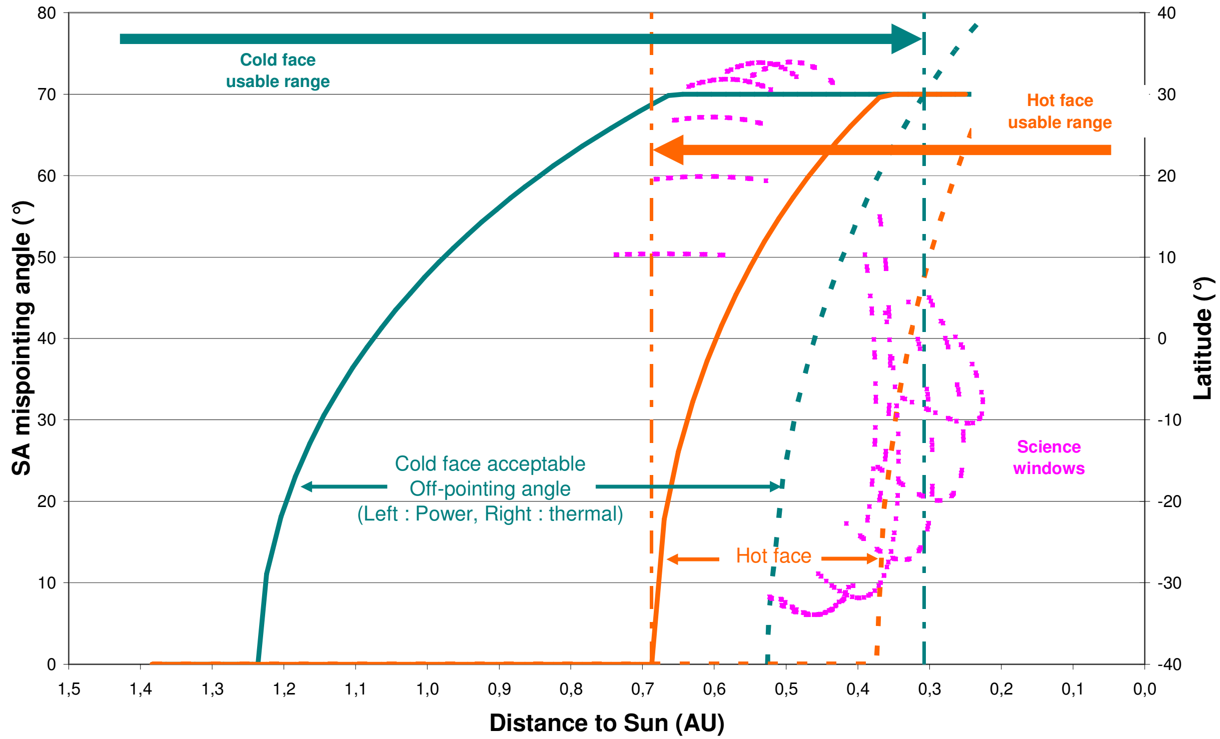
RPE requirement 1 arcsec over 10 s

Power Subsystem

- Fully regulated bus 28 V
- Power subsystem highly based on Bepi Colombo reuse
- Solar Array : Bepi Colombo double face panels
  - Cold face : used at large solar distance, with 100% cells ratio
  - Hot face : used in the hot case, with reduced cells ratio ~30%
  - ~6 m² solar panels driven by cold case
- Temperature control (200°C hot case) through Solar Arrays inclination up to 70° : key enabling technology





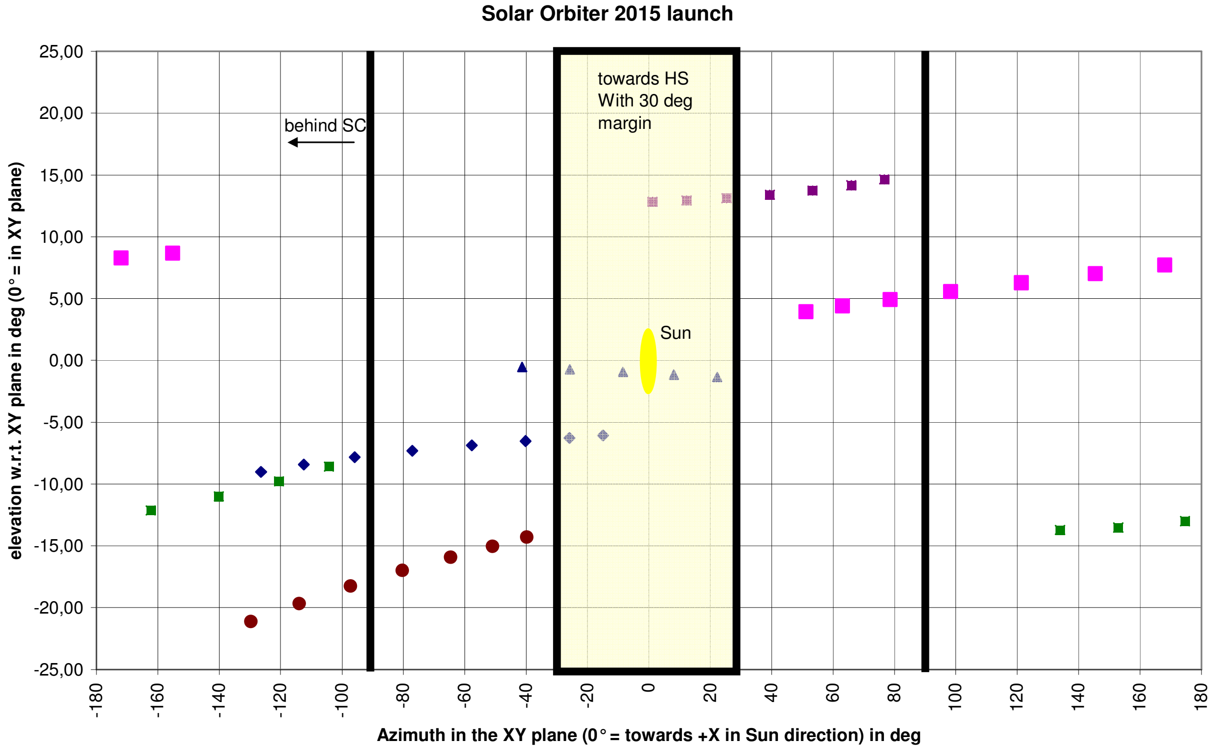


Communications Trade-off

- Requirements:
  200 kbps @ 1AU,
  no outage, X+Ka,
  + Doppler
  + Range tracking
  + ΔDOR

- HGA reuse from Bepi Colombo

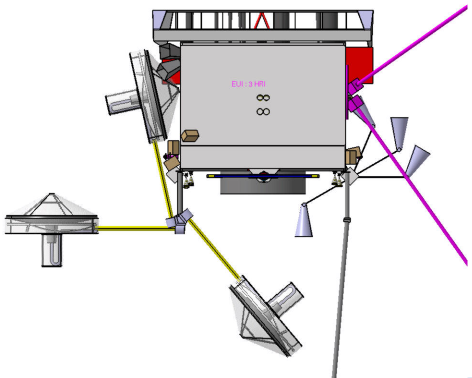
- X + Ka band rather than X alone

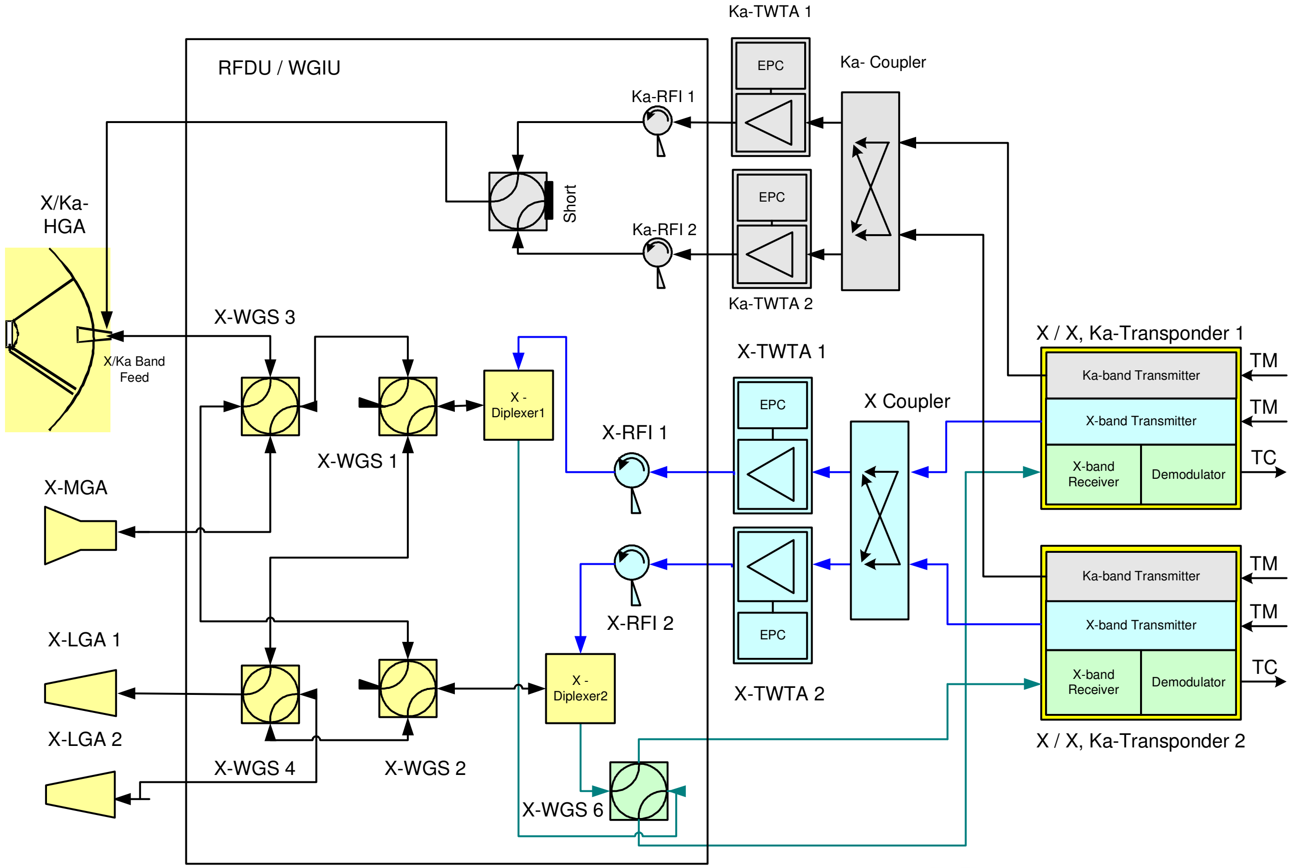


- HGA configuration options:
  - Brand new design for full performance at 0.2 AU (off-axis antenna, RF transparent shield)
  - Reduced performance at 0.2 AU with Bepi Colombo HGA (due beam off-pointing)
  - Bepi HGA communicating under spacecraft shadow (8 days outage at Perihelion 3)
  - No communication under 0.3 AU
- MGA configuration options
  - Use in safe modes (Earth strobing mode as on Rosetta)
  - Replacement of HGA under 0.3 AU

Communications Subsystem

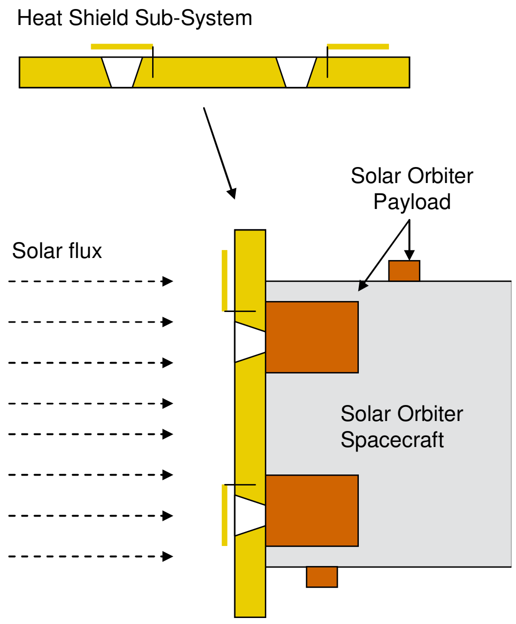
- Full recurrence with Bepi Colombo subsystem
- X + Ka downlink and X uplink
- 2 axes mechanism for HGA, 1 axis for MGA
- Bepi Colombo HGA

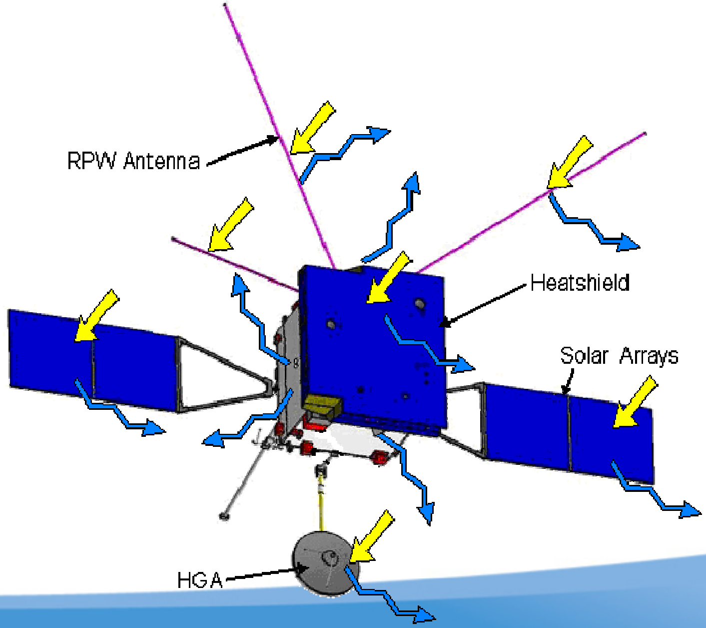


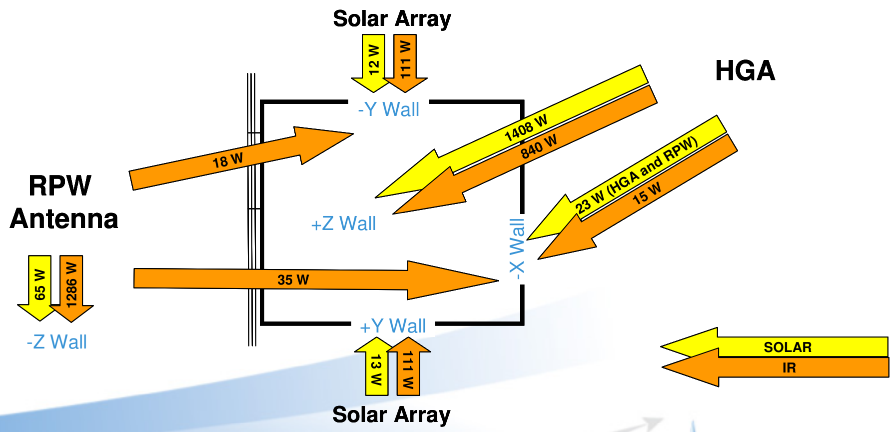


Thermal control Subsystem

- Thermal control based on a heat shield & permanent SC pointing towards Sun.
- Behind the Heat Shield, the spacecraft thermal control techniques are very similar to Vex / Bepi Colombo:
  - High temperature MLI to protect spacecraft wall from large flux rejected by appendages
  - Dedicated radiators for remote sensing payloads (hot interface and cold interface)
  - Access to cold space view factor for in-Situ instruments mounted on spacecraft wall, under heat shield shadow

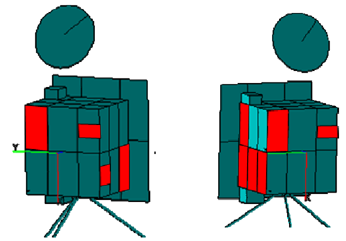


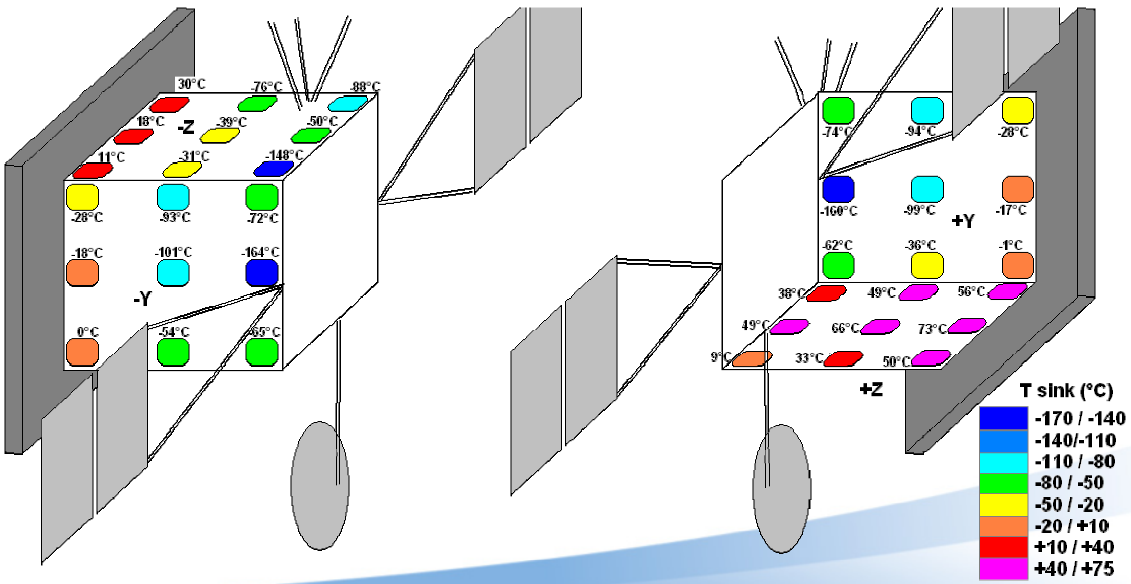




Thermal control Subsystem

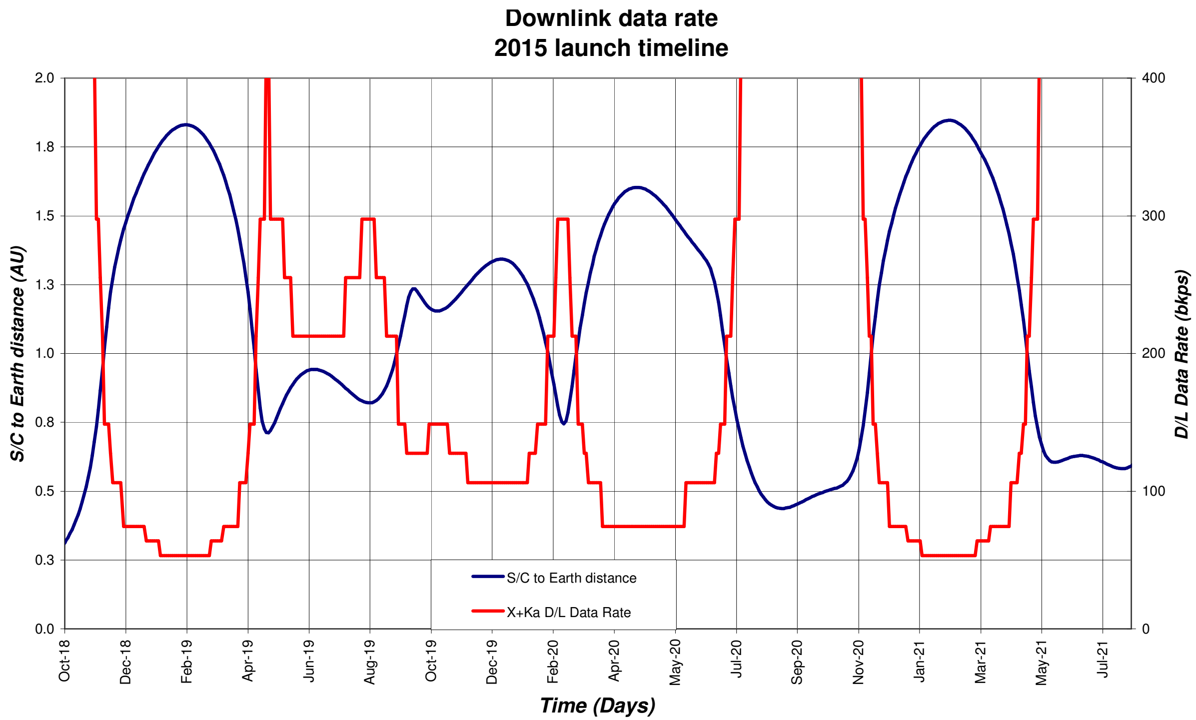
- Radiators sizing : 2.8 m² (none on HGA and RPW faces)
- Heating power : 400 W at 1.5 AU (worst case)
- High uncertainties on flux from appendages, with impacts on radiators location and system work:
  - Heat pipes between walls to transfer flux from payloads + equipments to faces not impacted by appendages
  - Off-pointing analysis : no off-pointing below 1 AU on Y faces (SA)
  - Sink temperature estimated for all surfaces of the spacecraft





Spacecraft budgets

- Power budget: 965 W in science mode, 800 W in safe mode
- Link budget : 200 kbps @ 1 AU is met in cold case.
- SSMM : 360 Gbits MOL
- Delta-V : 320 m/s in 2015, 160 m/s in 2017
- Mass properties:
  - Dry mass: 1015 kg inc 20% system margin
  - Propellant : 252 kg (2015) and 156 kg (2017)
  - Launch margin : 30 kg (2015) / 50 kg (2017)



2015 launch baseline

Propellant	1	including 20 days LW	252,4	0%	252,4
Total wet Mass					**1267,5**
Launcher adapter			*34,2*	*20%*	41,0
Total Launch mass					**1308,5**
LV performance		*including 20 days LW*			1339,1
Launch margin					**30,5**

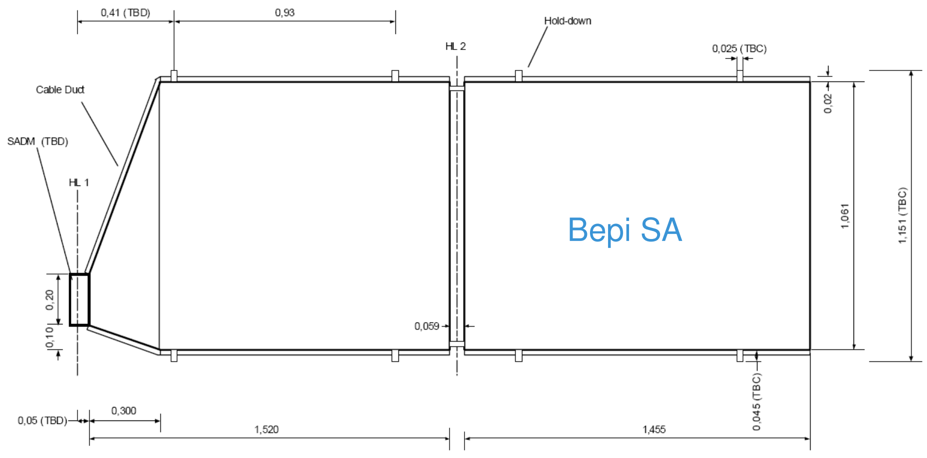
2017 launch backup

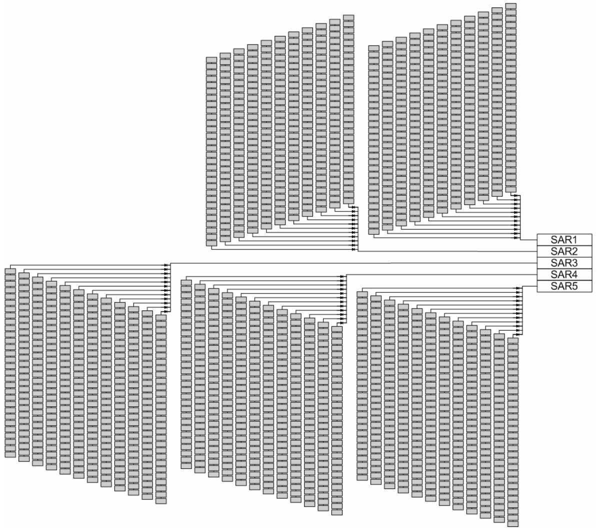
Propellant	1	including 20 days LW	155,5	0%	155,5
Total wet Mass					**1170,7**
Launcher adapter			*34,2*	*20%*	41,0
Total Launch mass					**1211,7**
LV performance		*including 20 days LW*			1261,7
Launch margin					**50,0**

Proposed heritage

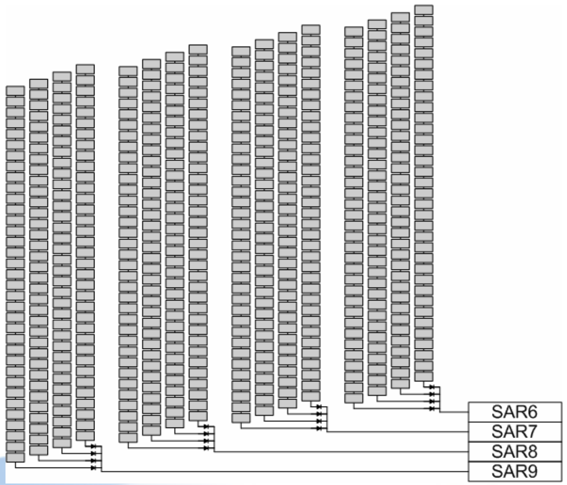
Element	mission	heritage
Structure	Venus Express	High heritage
DMS	OBC: Bepi Colombo RIU : Bepi Colombo SSMM : Bepi Colombo	OBC: reuse RIU : minor modifications SSMM : minor modifications
Communications	Transponders : Bepi Colombo RFDU : Bepi Colombo TWTA : Bepi Colombo HGA : Bepi Colombo MGA : Bepi Colombo LGA : Bepi Colombo	Transponders : reuse RFDU : reuse TWTA : reuse HGA MGA LGA : reuse
propulsion	Tanks: Herschel/Planck	Standard technology
AOCS	Gyros: Planck / Pleiades Star Tracker: Bepi Colombo Sun Sensor: Bepi Colombo Wheels: product (Teldix) 1-axis Gyro : product (Litef)	Gyros: reuse Star Tracker: reuse Sun Sensor: reuse + Δqual Wheels: Standard 1-axis Gyro : Standard
Power	PCDU : Bepi Colombo Battery : MEx / Vex / Aeolus / Goce SA : Bepi Colombo	PCDU : minor modifications Battery : state of the art SA : technology reuse
Thermal	VHT MLI : dedicated HT MLI : Bepi Colombo Heat shield : dedicated	VHT MLI : dedicated HT MLI : Bepi Colombo Heat shield : dedicated

Enabling technologies: SA



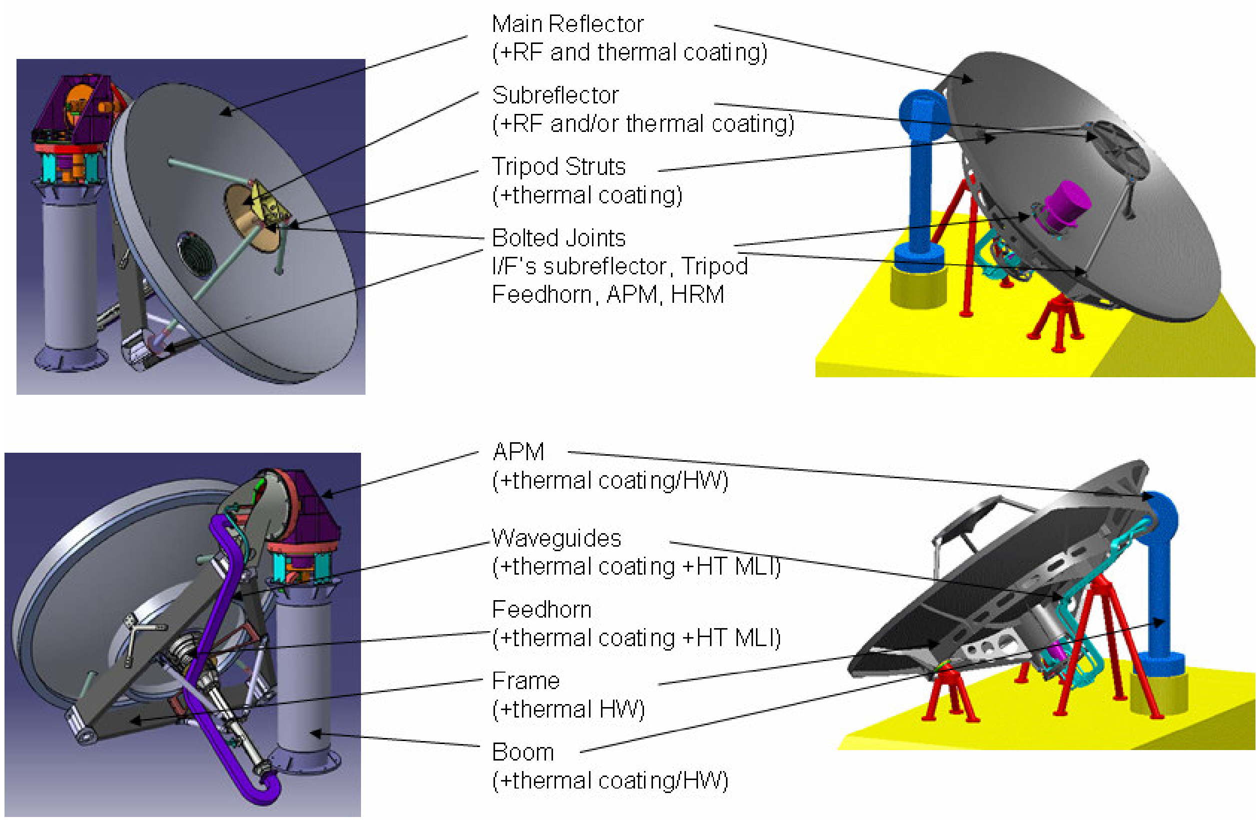


Solar Orbiter Sizing



- TJ GaInP2/GaAs/Ge cells with CMX cover glass
- Shunt diodes: separated ESA TDA.
- Blocking diode: separated TDA
- Challenges:
  - 70 deg off-pointing – thermal management: 65 deg in test for Bepi
  - Qualification for extended Solar Orbiter ageing (250,000 esh)

Current BC HGA Concepts – Critical Elements



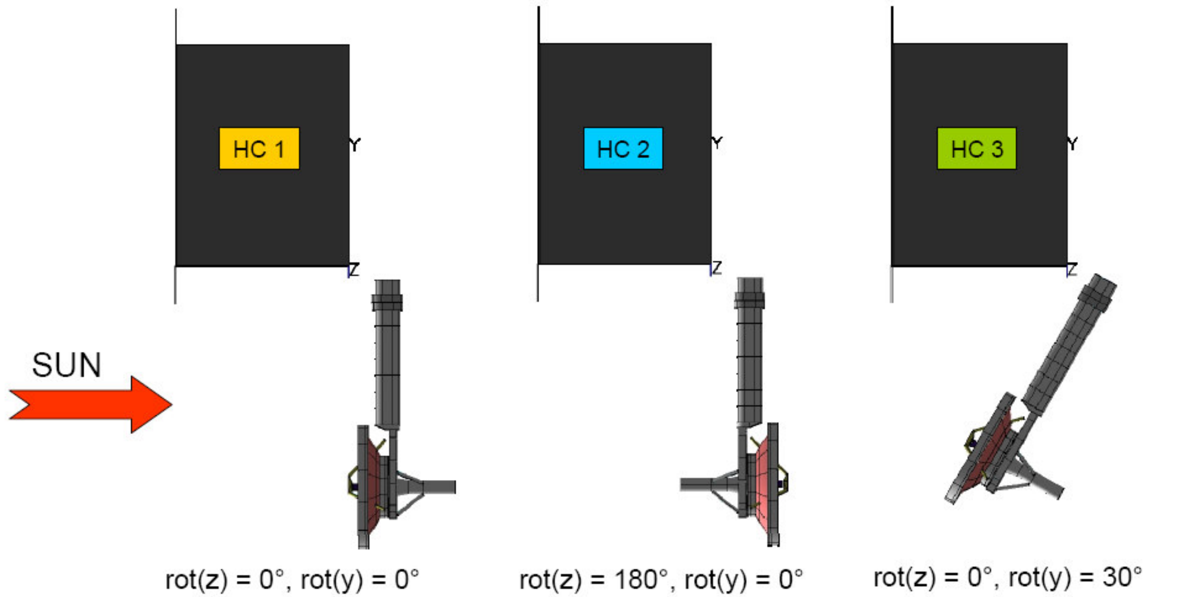
- Material Technologies
- RF and thermal coatings
- Joining technology

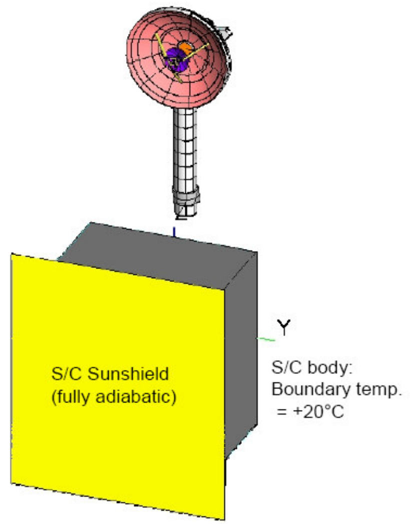
Reuse of BC antenna on SolO

- Thermal analyses in hot cases: at 0.22 AU

- Objectives:
  - Investigate limits of Bepi Colombo HGA design under Solar Orbiter environment
  - Propose recommendations for hot spots

- Enabled investigation on Bepi Colombo antenna reuse

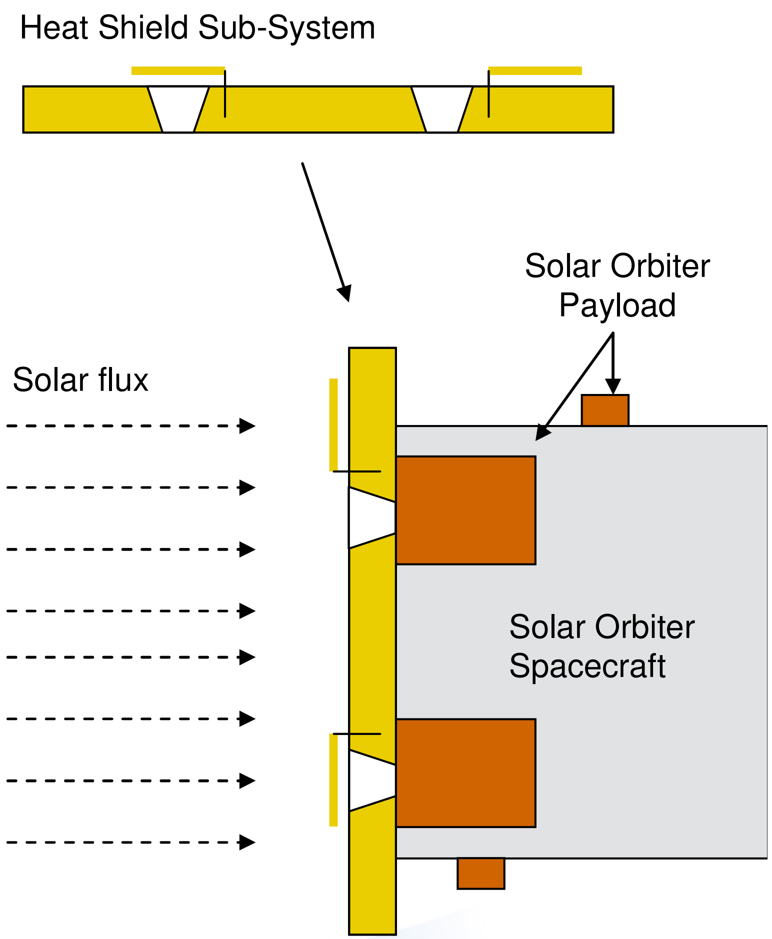




Heat Shield

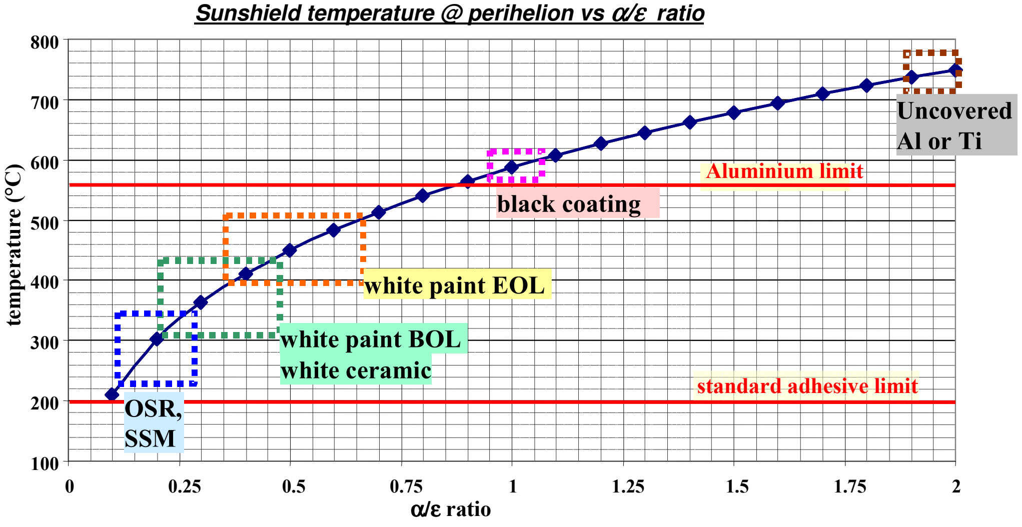
Heat Shield Requirements

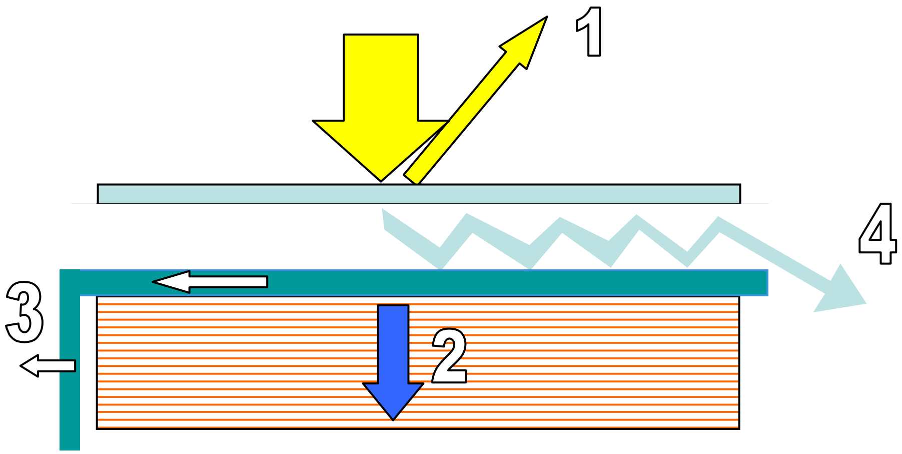
- Subsystem, to be tested prior integration
- Provide shadow with 5 deg half cone angle
- Provide for unobstructed FOV for payloads +
  - Thermal baffles if required
  - Doors + mechanisms
  - Alignment between FOVs
- Heat fluxes at 0.22 AU:
  - Radiative to SC X wall < 15 W/m²
  - Conductive to SC X wall < 18 W
  - To instruments cavities : per instrument
  - Radiative to lateral walls
- Interfaces: 80 kg target
- Design : structural frequencies, static loads, thermal loads, …



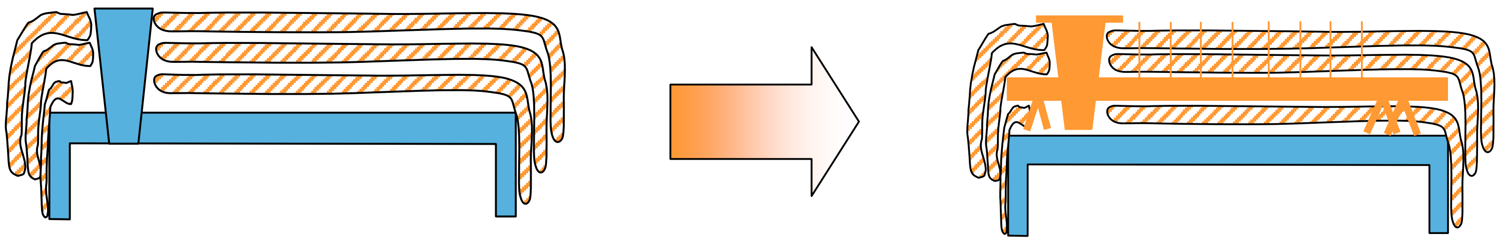
Heat Shield thermal trade-off

- Previous assessment studies:
  - Flat heat shield,
  - Launch configuration on top of spacecraft,
  - External layer coating drives temperature:
- Thermal options:
  - Radiative insulation : MLI effect
  - Conductive transport to lateral radiators
  - Radiative transport to cold space through multi-reflections effect
- Thermal trades :
  - lateral conduction (weight)
  - MLI vs Sunshade (weight + height)
  - External coating (ageing)
- MLI vs Sunshade

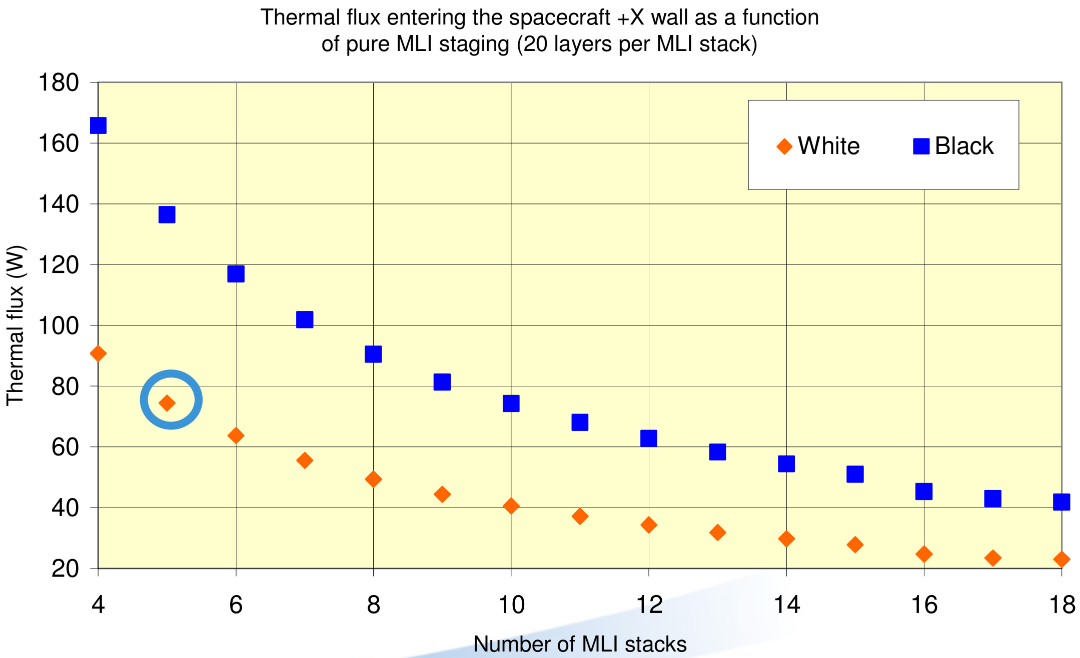




Heat Shield MLI option

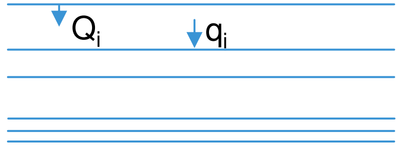


- Heat shield shall be tested separately + hot baffles => intermediate structure
- 1-D MLI modelling (pending on efficiency assumptions):
  - White only for low mass
  - 80 kg heat shield with 5 stacks, 75 W entering SC
- High uncertainties
- Low evolution margins
- Only 3/4 potential tools for flux management are used



Heat Shield sunshade option

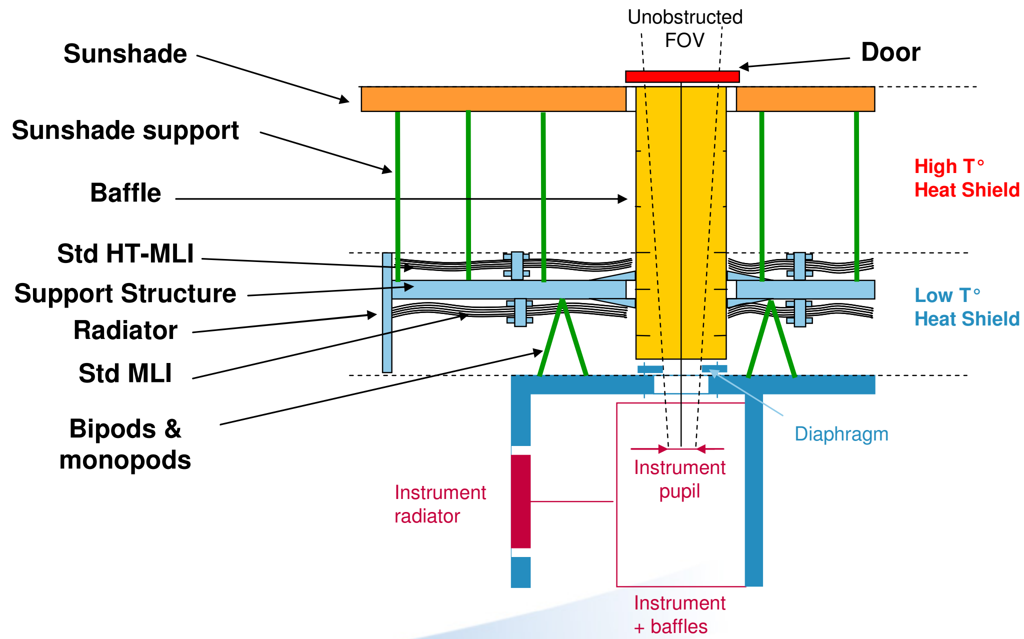
- Radiative lateral transfer:
  - Optimal efficiency with N equally spaced layers (Lagrange optimisation with boundary limits external layer / spacecraft)
  - Flat layers can be as efficient V-shape pending on height
  - Number of layers N is a function of emissivity



N layers
μ_i geometry factor = f(h_i)

$$\mu = \frac{1 + K\left(\frac{q}{Q}\right)^{1/N}}{\left[1 - \left(\frac{q}{Q}\right)^{1/N}\right]\left[K - 1\right]}$$

- Conclusions :
  - Sunshade can be a single flat layer or a group of layers (MLI)
  - White coating, single layer: two cavities
  - **Black coating, MLI: 1 single cavity**
- Versatile : height can be tuned as a function of thermo-optical properties of elements
- Radiative transfer in high T° domain, standard conductive + radiative one in low T° domain



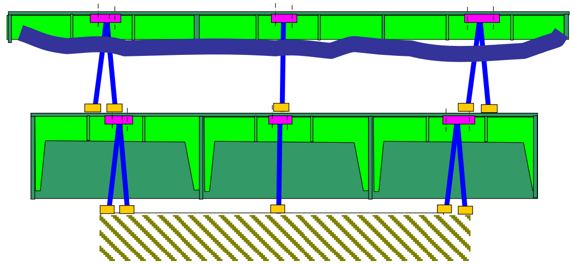
EADS astrium

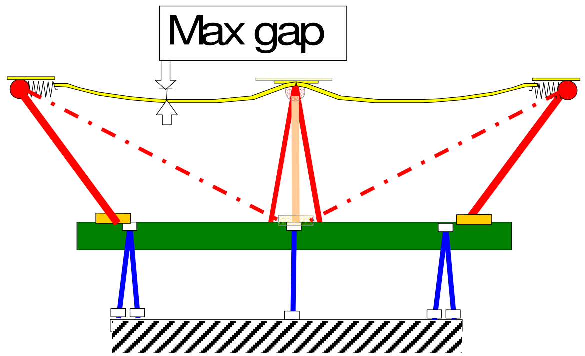
Heat Shield mechanical trade-off

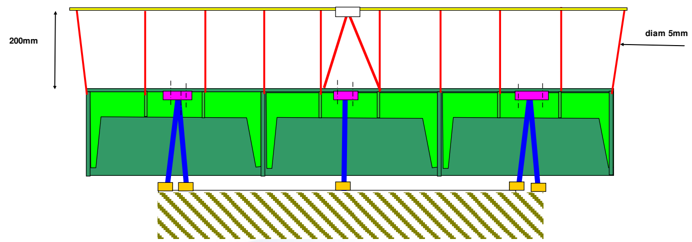
- Support structure optimized for low CTE, high conduction, high stiffness, low mass
  - Aluminium is simplest, lower cost
  - Future optimisations: Al vs C/C

- Sunshade driver = thermo-elastic deformation
  - Rigid sunshade, low CTE:
    - highest mass
    - potential highest performance in thermo-elastic
  - Flexible sunshade 1 layer (white) + springs:
    - Based on pre-loaded springs on rods
    - sized to minimize gap under thermal and launch loads
  - Flexible sunshade MLI on rods:
    - based on laterally pre-loaded thin rods
    - sized to absorb thermo-elastic deformations and minimize thermal conduction

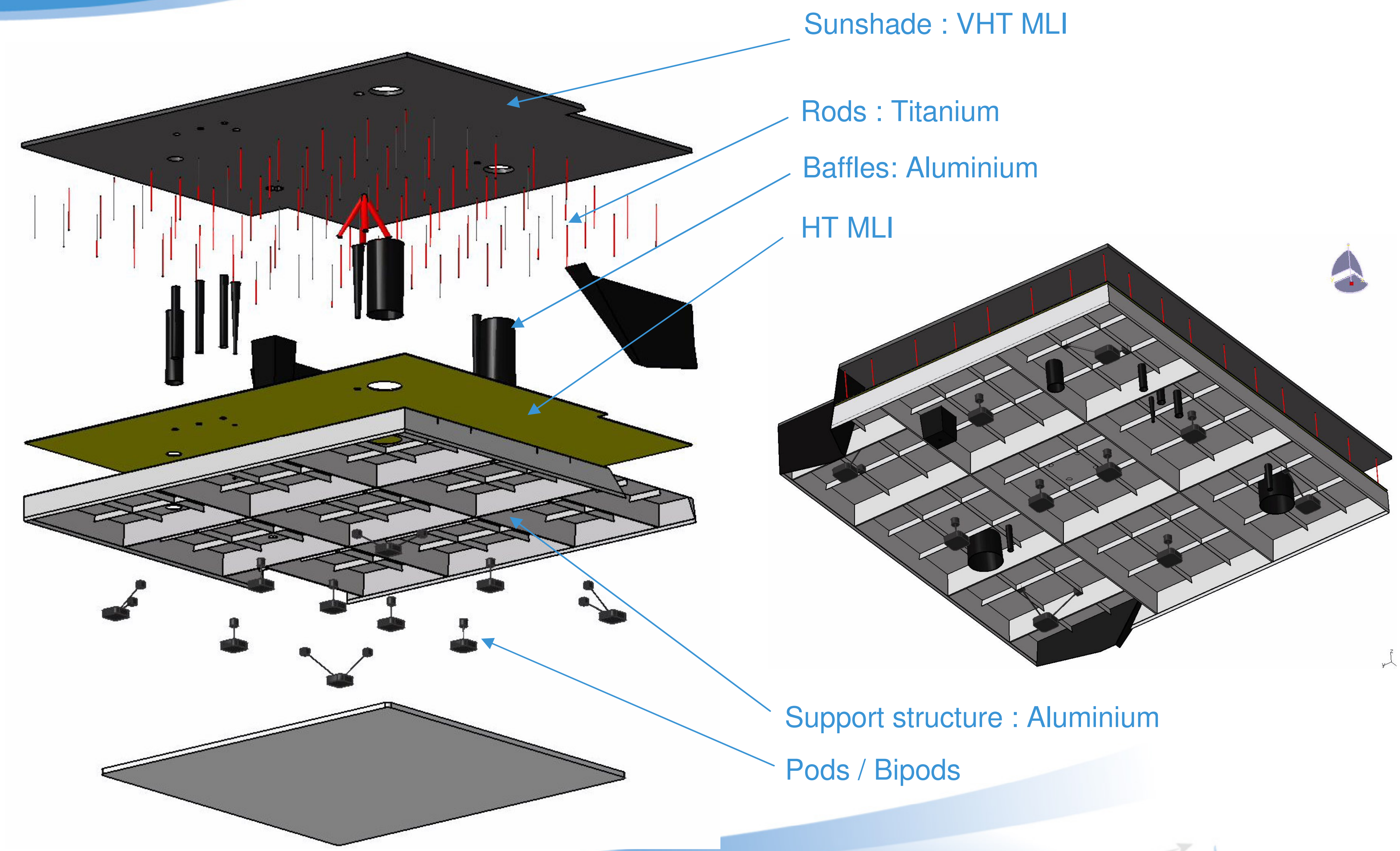
- Best rated = flexible MLI sunshade on rods





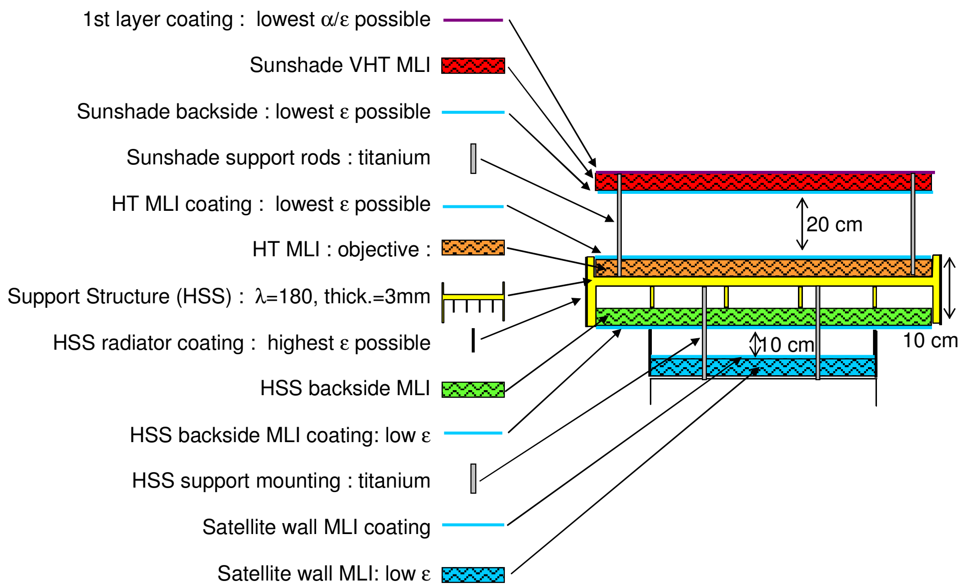


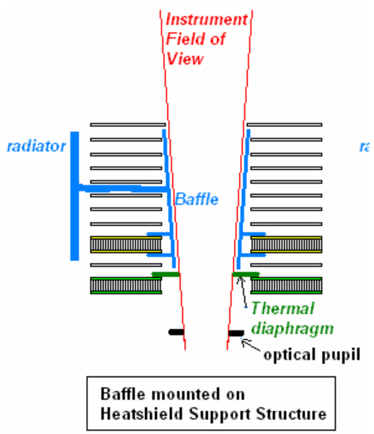
Heat Shield configuration

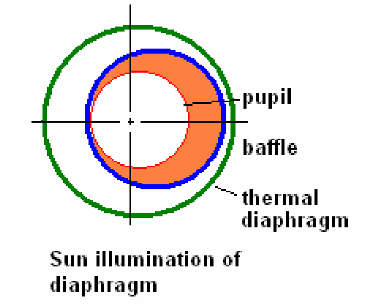


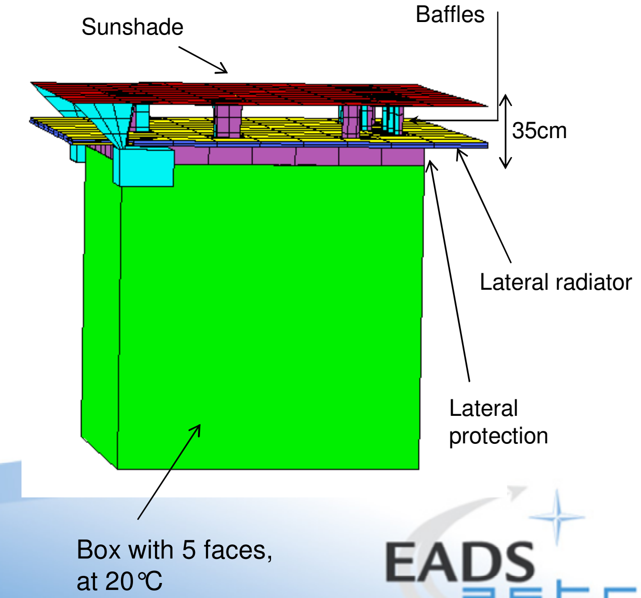
Heat Shield thermal design

- Thermal architecture:
  - 1 Single cavity, black coating
  - Coating trade: Black Keplacoat®
  - VHT MLI : titanium layers with tissueglass spacer
- Baffles design
  - Aluminium, black coated, top ring in sunshade material
  - Mounted on support structure
  - FOV including margins for thermo-elastic deformation of support structure





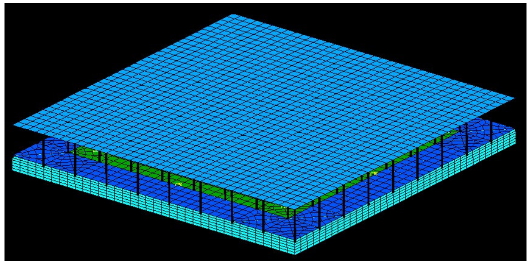


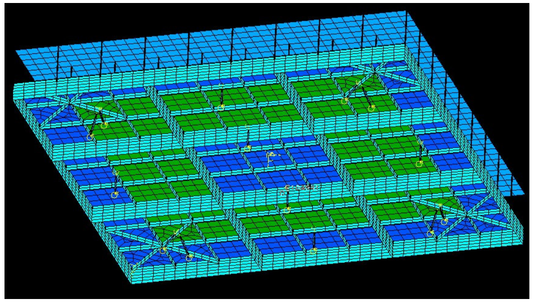


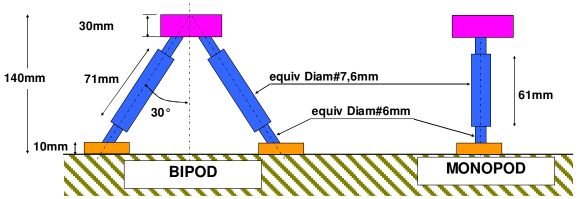
Heat Shield mechanical design

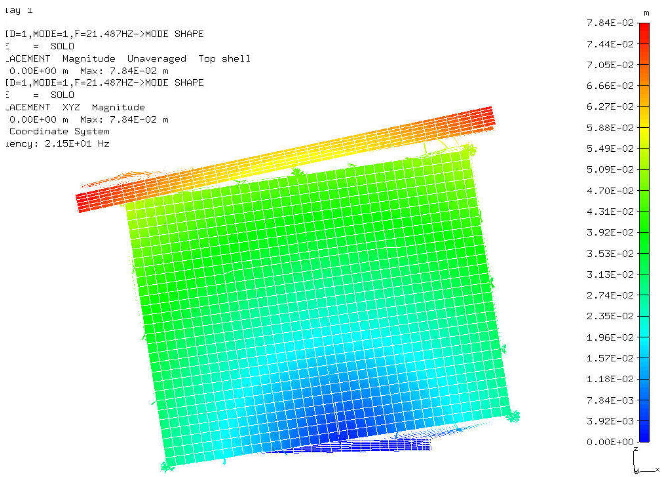
- Support structure design:
  - aluminium stiffened skin
  - 4 Ti bipods + 6 monopod (to break the longitudinal mode) interfacing with spacecraft corner & wall
  - Supports sized for 25 g static loads and thermo-elastic
- Heat Shield FEM and modal analyses
  - Lateral >> 20 Hz
  - Longitudinal > 50 Hz
- Spacecraft FEM for mechanical analysis at system level
- Heat shield mass ~ 80 kg with maturity margin 25 %

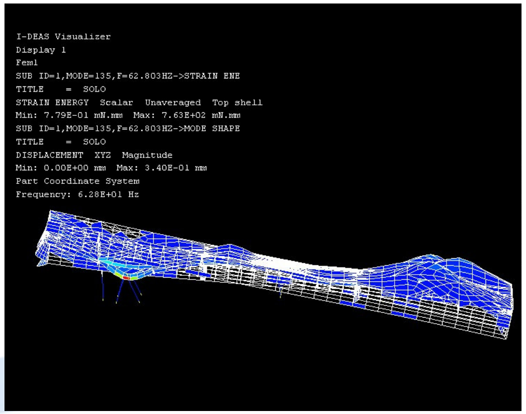
	FEM mass
sunshade = Ti foil with ,219mm total thickness in Ti (density artificially increased for margins)	17,4
baffle + motor+structure reinforcment= structural distributed mass including uncertainties	15,0
100 lash of Ti diam 5mm	1,9
structure (skin 1,5mm+ extended stiffeners1,5mm)	31,1
total mass=	**65,4**





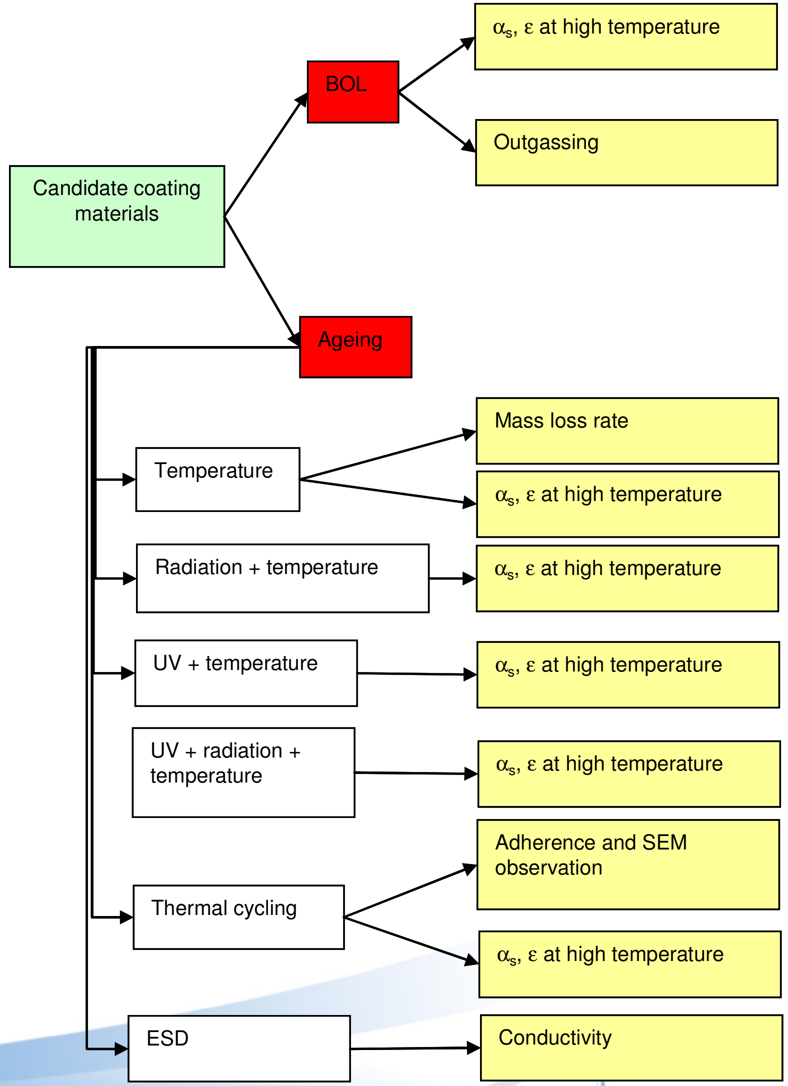






Heat Shield concept validation

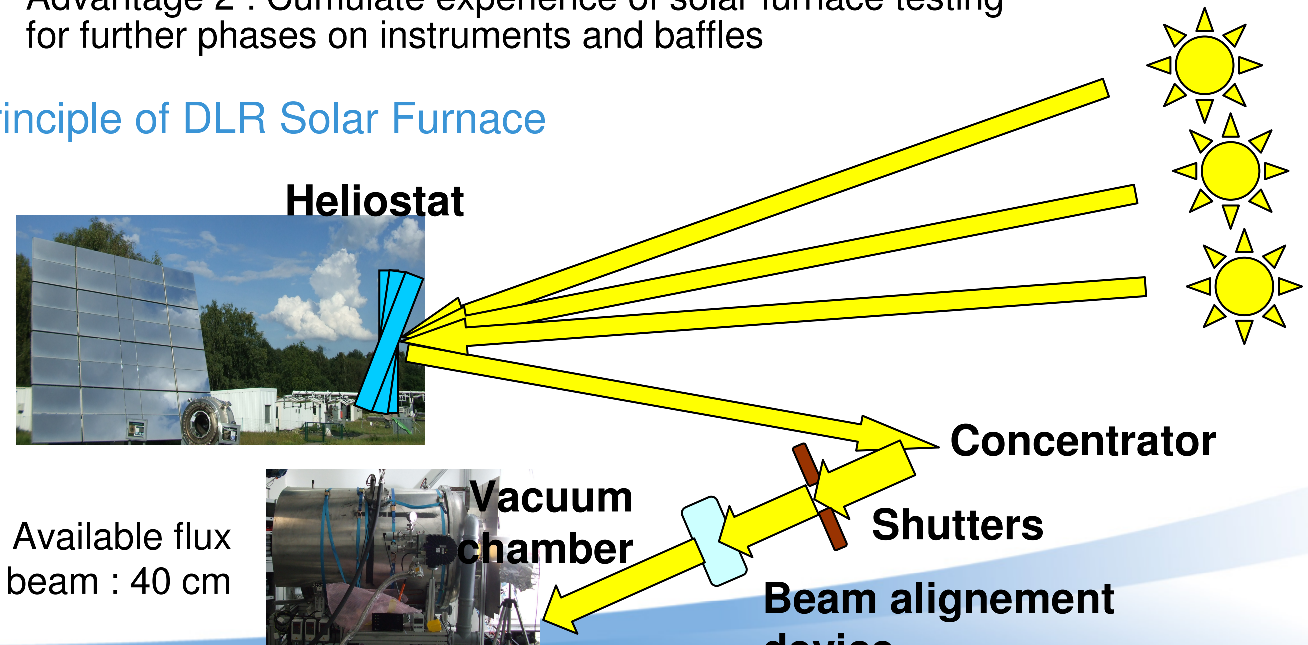
- Coating validation:
  - During the study : Thermo-optical properties characterization for Black Keplacoat® external layer and for Titanium internal layers
  - A full test plan for future coating validation has been setup
- Breadboard test programme
  - Objective is to demonstrate Heat shield concept validity and measure main parameters in conditions as close as possible from flight
  - Options: IR tests (non representative spectrum), Artificial lamp test (high power required), Solar furnace test (limited chamber size)



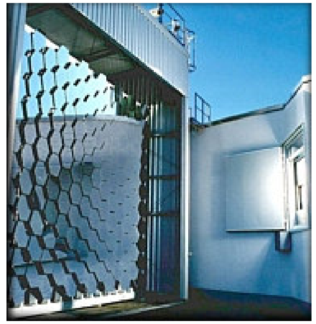
Breadboard test with real Sun

- Trade off : test with artificial lamps or in real solar flux ?
  - To be able to have correct material behaviour depending on α, ε and temperature, the test is performed in a solar furnace
  - The largest available vacuum chamber combined to a solar concentrator is in DLR Cologne
  - Advantage 1 : Same flux as perihelion, materials properties (α and ε) behave as in flight
  - Advantage 2 : Cumulate experience of solar furnace testing for further phases on instruments and baffles

- Principle of DLR Solar Furnace

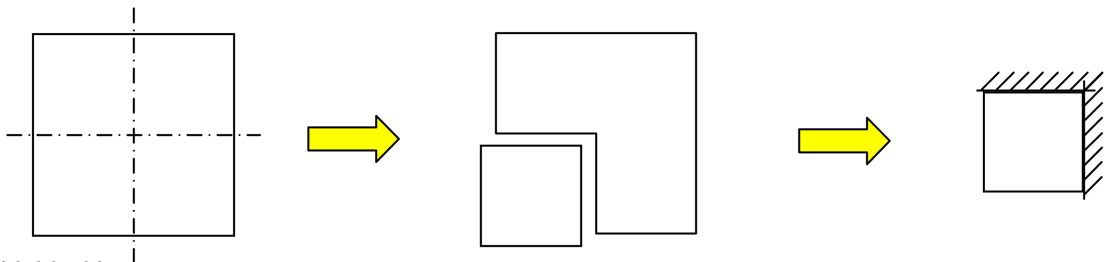


Available flux beam : 40 cm

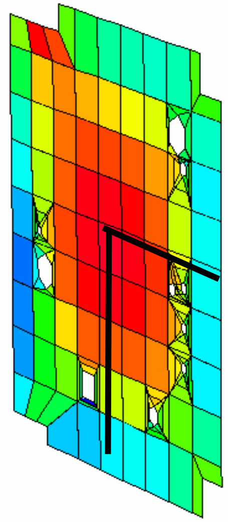


Breadboard main principles

- Trade off : scale 1 test or reduced scale ?
  - Scale 1:1 imposes very tight portion of heat shield in test chamber (40 cm diameter).
  - Scaling imposes tight constraints and challenge on thermal modelling
- Solution : Use of 2 symmetry walls
  - Only a quarter of the Heatshield is simulated, 2 symmetry walls allowing the restitution of the whole Heatshield behaviour.
  - These symmetry walls are made of high reflective aluminium surfaces thermally decoupled from the chamber and the breadboard structures.

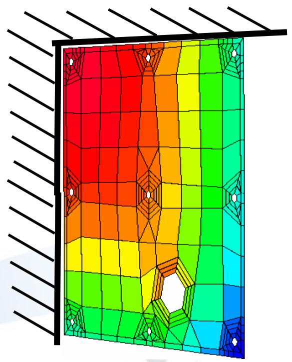


Heatshield with 2 symmetry axes



Heatshield predictions

Breadboard prediction

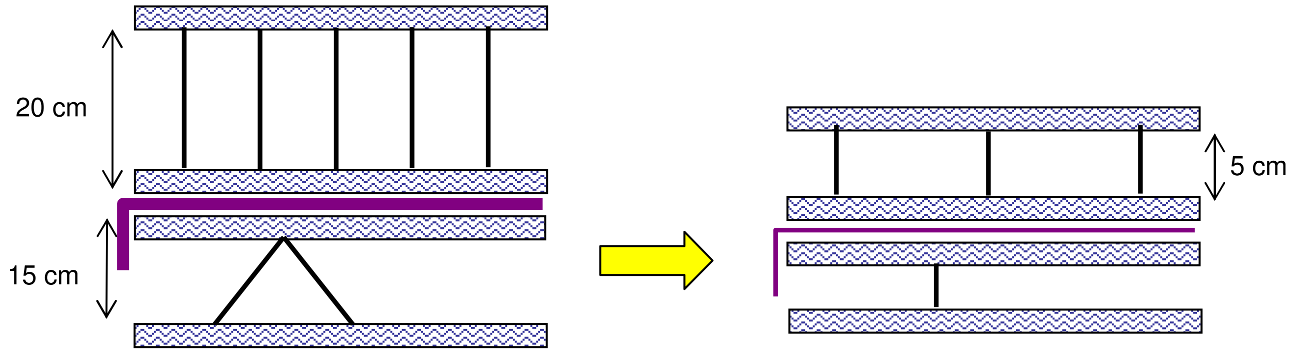


Breadboard main principles

- Scaling method

  - The breadboard dimensions are scaled of a factor 1/16 (¼ due to symmetry x ¼ due to scaling).

  - The scaling keeps the **same temperature maps and same flux densities** between reduced scale and full scale models. Conduction is adapted (radial and transverse) with a constant ratio $\lambda e/R^2$ in breadboard model as in full scale model.

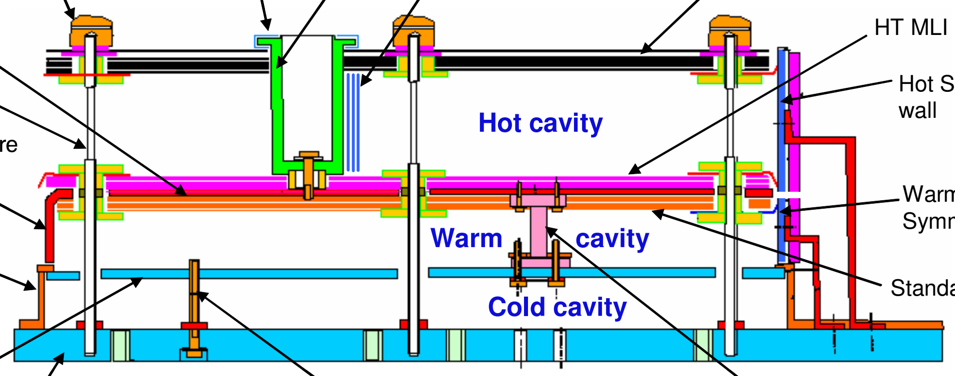


Heatshield dimensions *Breadboard dimensions*

  - At breadboard level, dimensions are reduced of a factor 16, and the same ration (radiative flux) / (conductive flux) ratio is kept as compared to flight model.

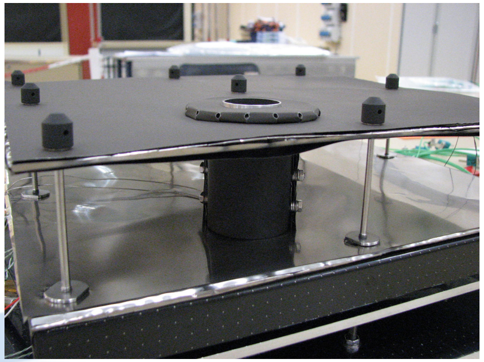
Breadboard design

- Breadboard design
  - 1 VHT MLI
  - 1 cavity laterally open
  - 1 HT MLI
  - 1 support structure with lateral radiator
  - 1 standard MLI
  - 1 sat wall



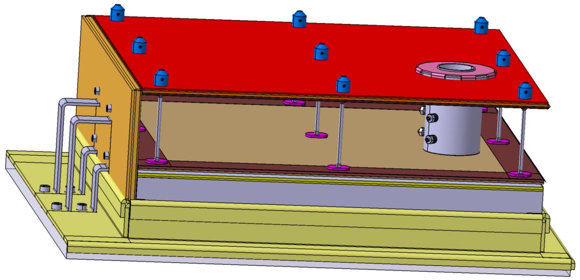
- 1 Baffle
  - Closed at support structure level (⇒ worst case of baffle)
  - Representative of all cumulated flight baffles (in term of flux)
  - Same interfaces as flight

- Titanium rods
  - 9 rods (same design as for flight) supports the VHT MLI. They are directly attached to the Back shroud

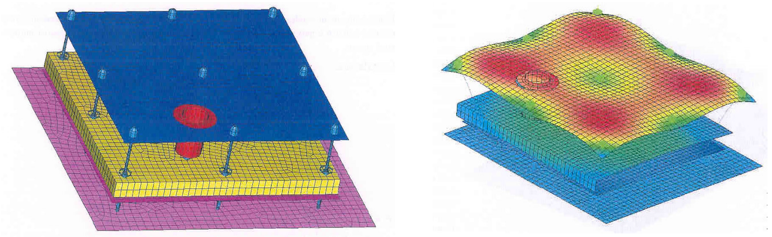


Breadboard before symmetry walls integration

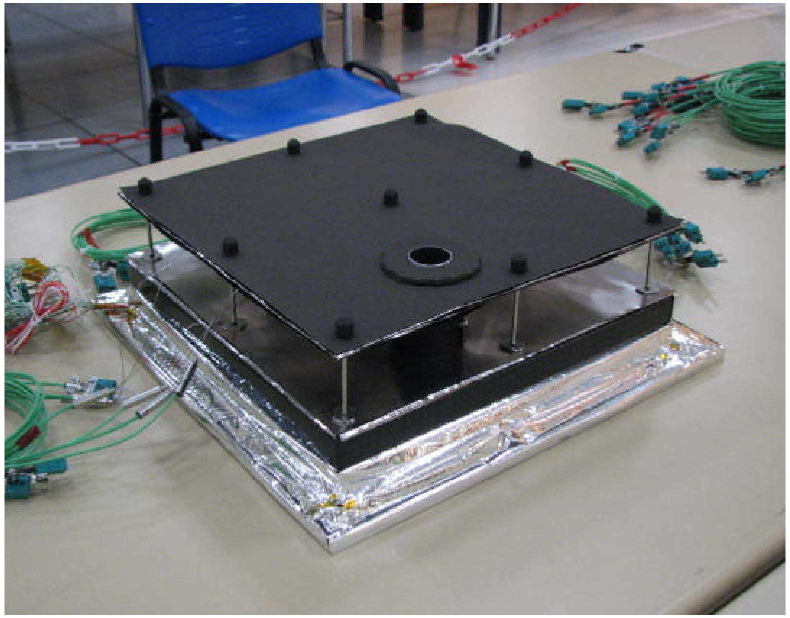
Breadboard manufacturing



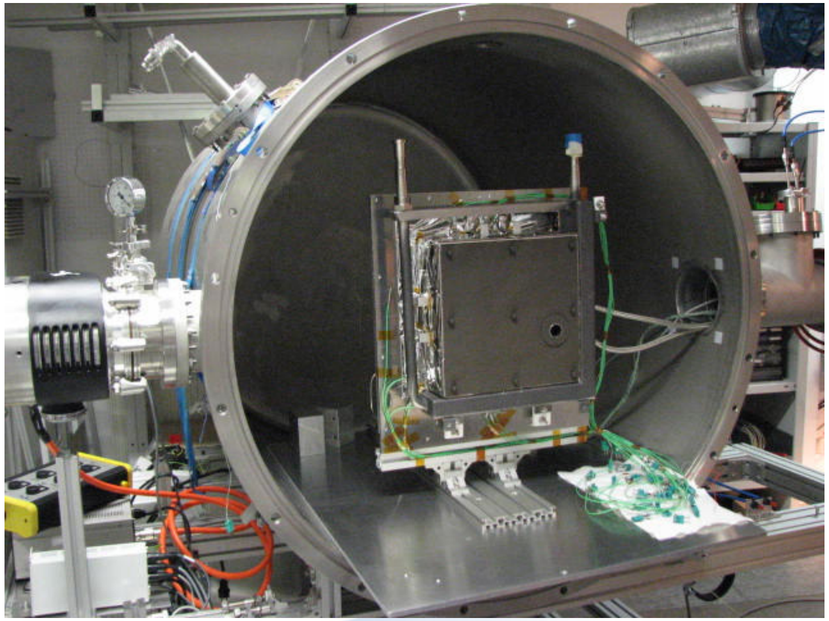
Breadboard drawings and configuration



Breadboard mechanical justification
under gravity and thermal loads



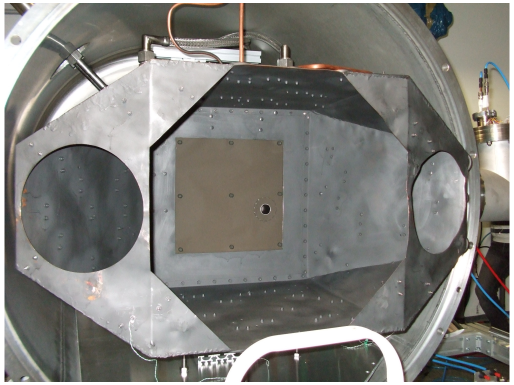
Breadboard integration in Toulouse



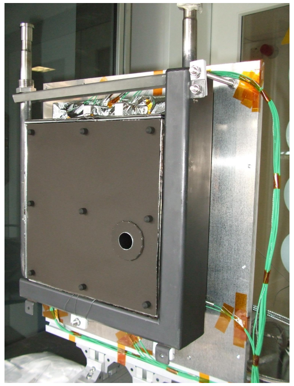
Breadboard integration in DLR

Breadboard test environment

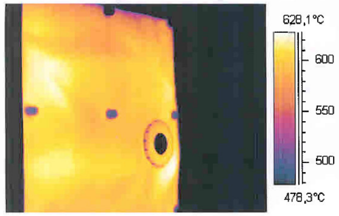
- Thermal shrouds
  - The Front Shroud is cooled with water with several apertures for Sun flux, video and infrared cameras.
  - The lateral rejection of flux is absorbed by the LN2 Lateral Shroud.
  - The Back Shroud ensured stabilised 20°C, which simulates the satellite cavity.
- Sun flux
  - An homogeneous flux of 28 kW is send on the breadboard
- Monitoring
  - Temperature are recorded with 40 thermocouples
  - + an infrared camera (calibrated for keplacoat at high temperature)
  - A video camera allowed to film and record the deformation of the front part.



The Breadboard and its Front Shroud in DLR chamber



The Breadboard and its Lateral Shroud in DLR chamber



Infrared thermography of the Breadboard under 28 kW/m²

Video monitoring of the Breadboard under 28 kW/m²

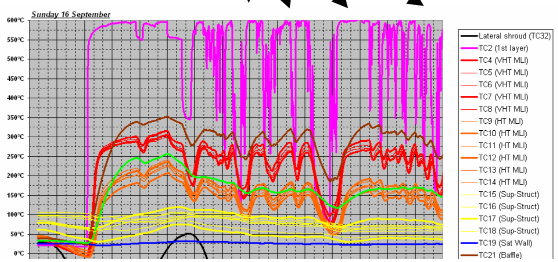
Breadboard tests overview

- 4 weeks under vacuum (< 10^{-4} mbar)
- 6 Sun tests have been performed
  - 6 Sun tests representing a total of 27 hours of Sun illumination
  - Several preheating tests (up to 150°C on Support Structure)

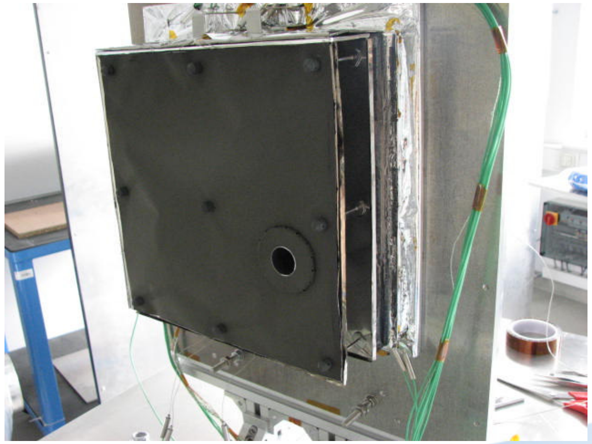
  ⇒ sufficient data for thermal model correlation

  ⇒ total of 27 hours of Sun illumination at 28 kW/m²

  + hundreds of thermal shocks (0 to 28 kW/m² on the Breadboard)



Example of Sun test with thermal shocks



Breadboard after tests

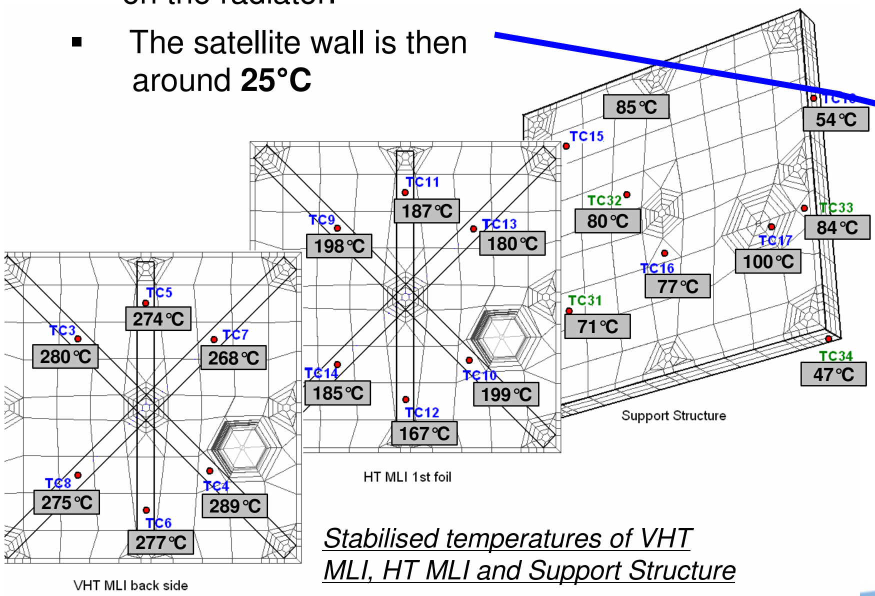
Beautiful Cologne sky…

EADS astrium

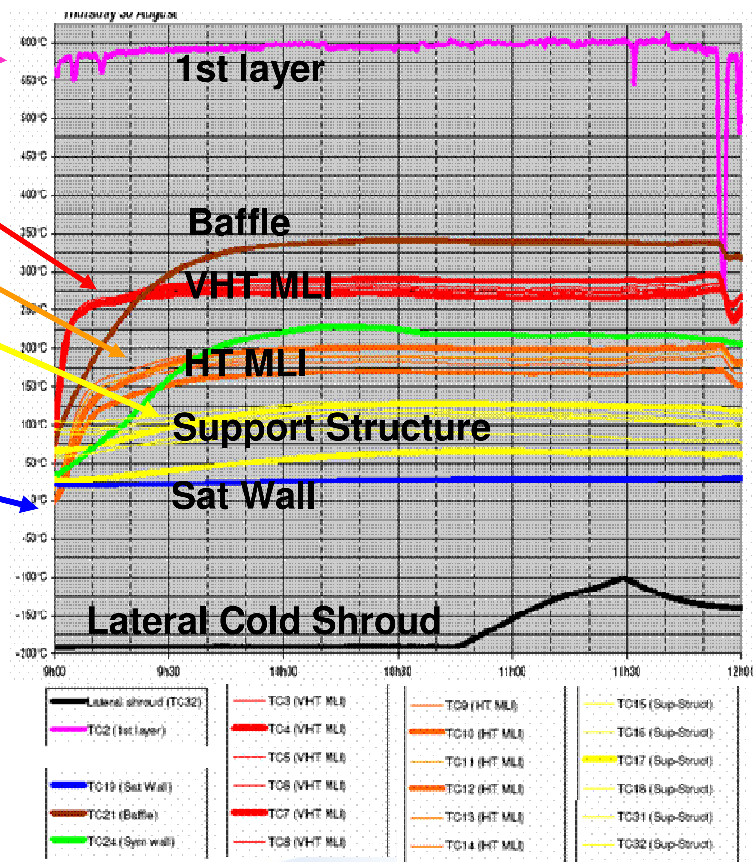
Breadboard test results

Very good behaviour of the breadboard, within the predicted temperature ranges (~colder due to higher efficiency of MLIs)

- The 1st illuminated layer stabilises around **610°C**
- A few millimetres behind, the last foil of the VHT MLI is at **280°C** (20°C of gradient inside the same foil)
- The HT MLI, facing this VHT MLI, is about 90°C colder, at **190°C** (23°C of gradient inside the same foil)
- A few millimetres behind, the structure Support stabilises between **100°C** (closed to the baffle interface) and 47°C on the radiator.
- The satellite wall is then around **25°C**



Stabilised temperatures of VHT MLI, HT MLI and Support Structure



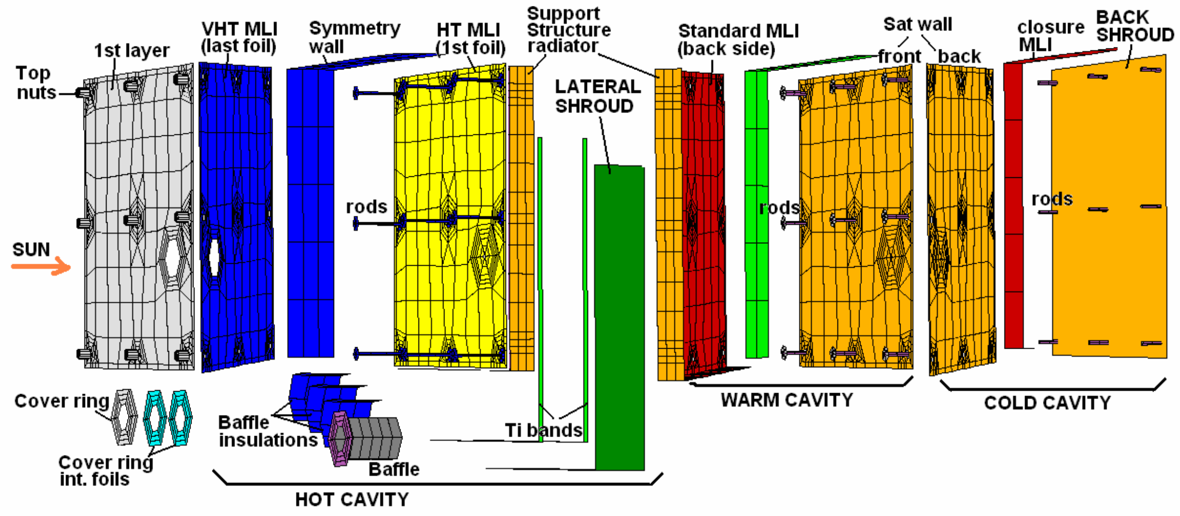
Temperatures variations after 3 hours of Sun illumination (30 Aug. 07 test)

EADS astrium

Breadboard model correlation

- A dedicated breadboard thermal model was built for tests predictions and test correlation

- Correlation uses :
  - the 6 Sun tests
  - the preheating tests



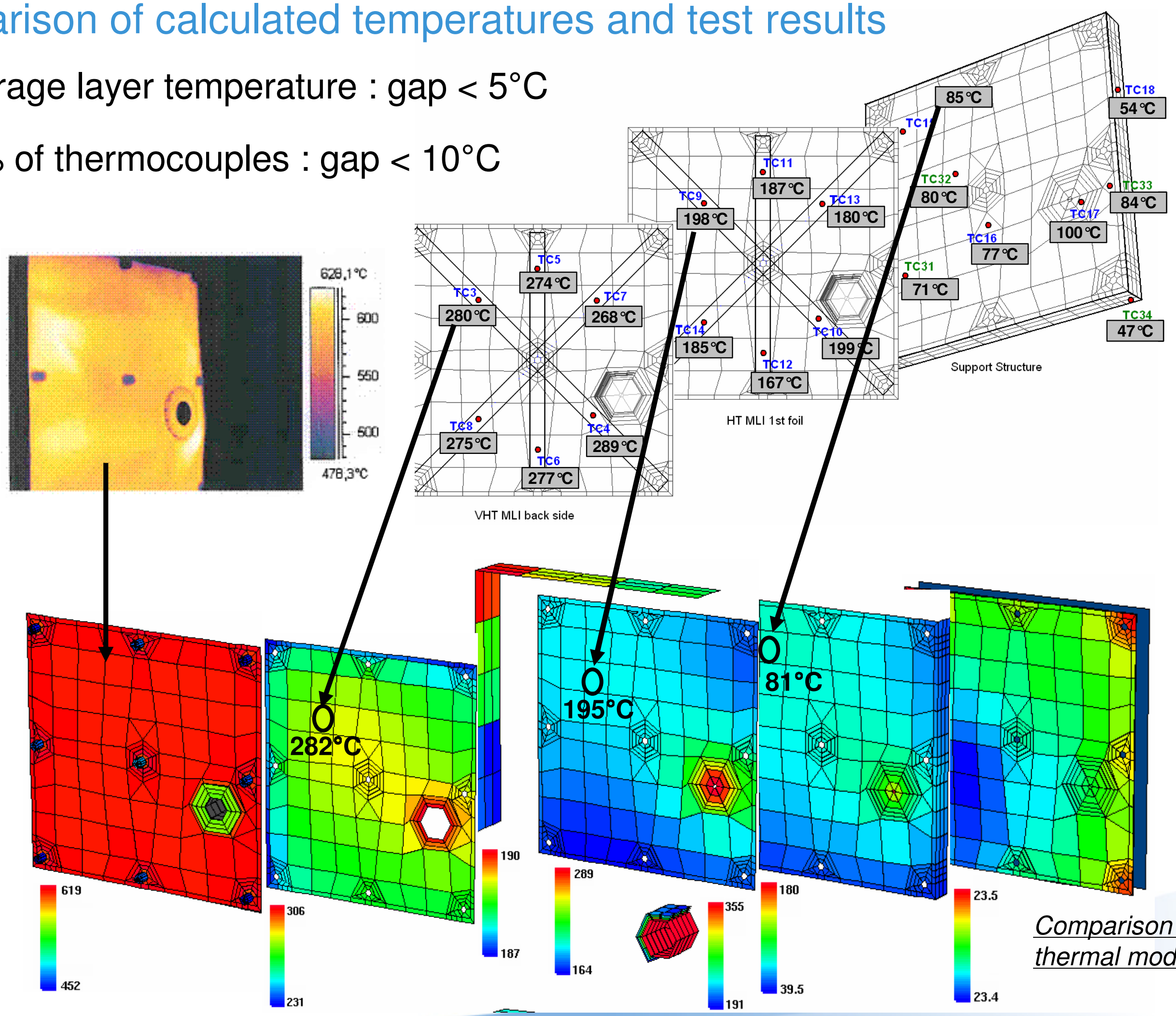
The breadboard thermal model (exploded view)

- Materials properties characterisation tests are performed in parallel :
  - Characterisation test of emissivity depending on the temperature, the angle, the wavelength… (titanium, Keplacoat®)
  - measurements of solar absorptivity

- Main outputs of the correlation after tests are MLI efficiencies.

Tests results

- Comparison of calculated temperatures and test results
  - Average layer temperature : gap < 5°C
  - 95% of thermocouples : gap < 10°C



Comparison between test results and thermal model predictions

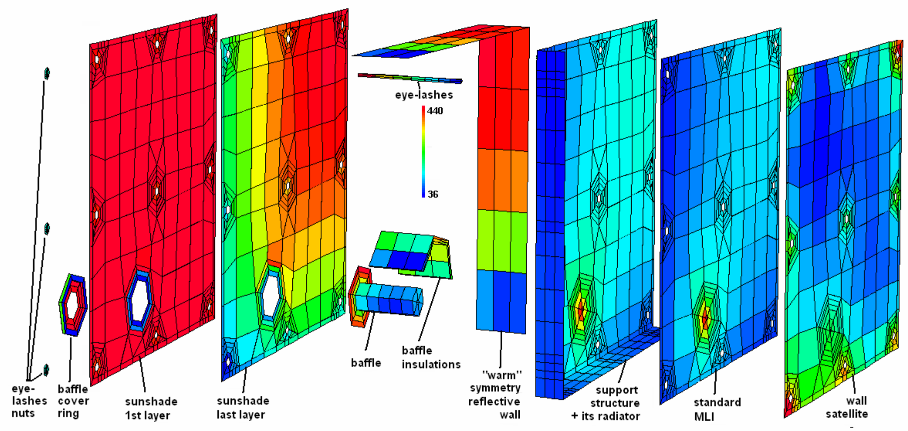
Tests findings

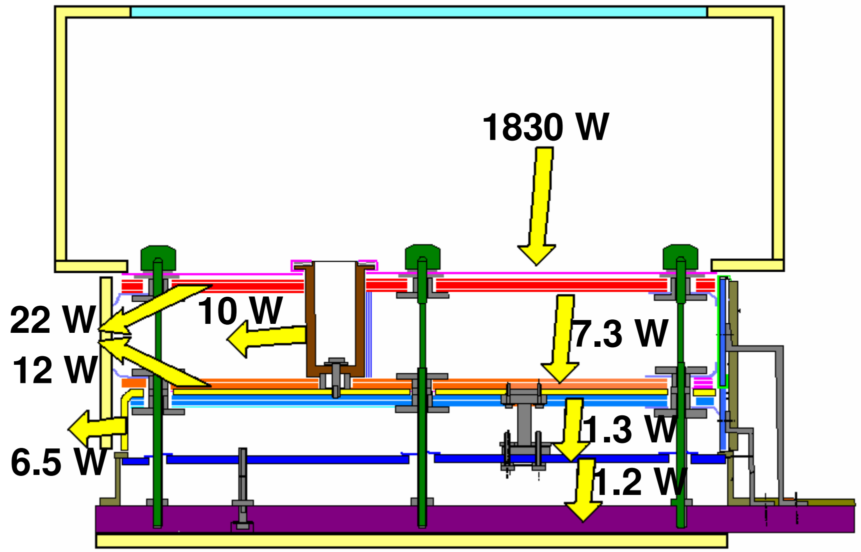
The lesson learnt is that the involved high temperature MLI has a very similar efficiency compared to a standard MLI.

- Correlated model flux exchange

  With the correlated model, we can compute all the flux exchanges inside the breadboard.

- Correlated model temperature map

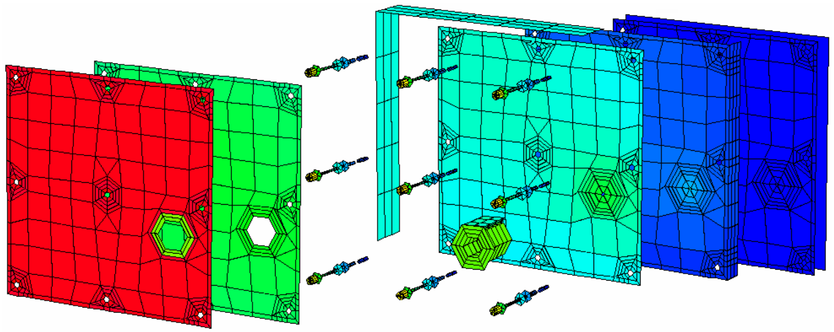


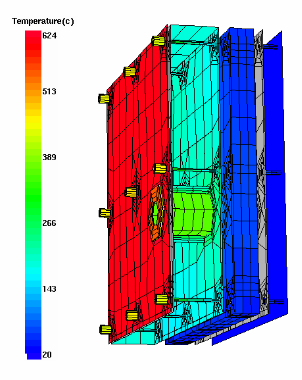


The thermal model provides a complete thermal map of the Breadboard.

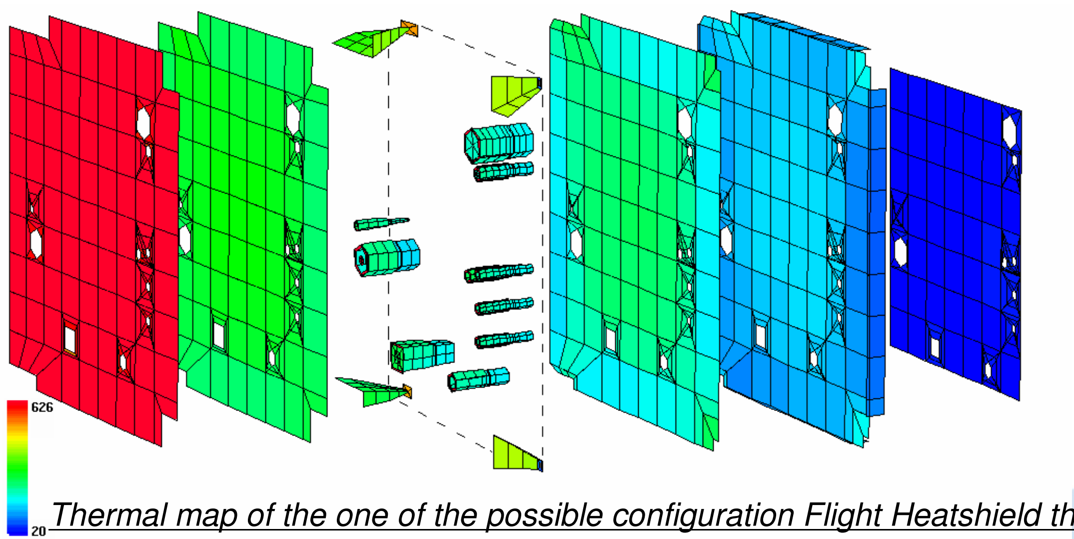
Breadboard vs Flight

A same scale of temperature is used for both model results, showing the similarity between breadboard and flight

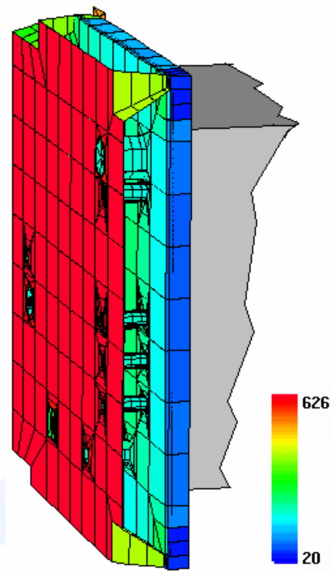




Test Heatshield breadboard thermal model (in hot case)

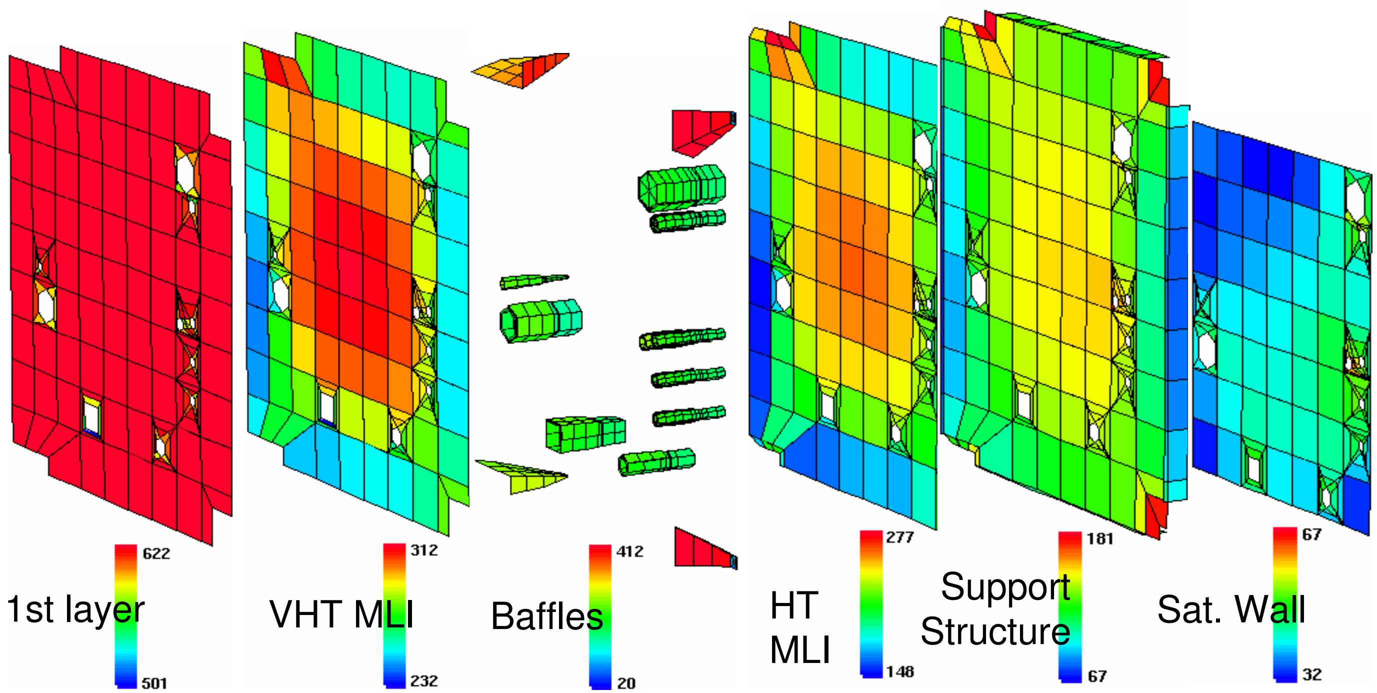


Thermal map of the one of the possible configuration Flight Heatshield thermal model (in hot case)



Heat Shield Performance

- Flight predictions after test model correlation: includes correlated test results and lessons learnt (with margin): MLI efficiencies, materials thermo-optical properties



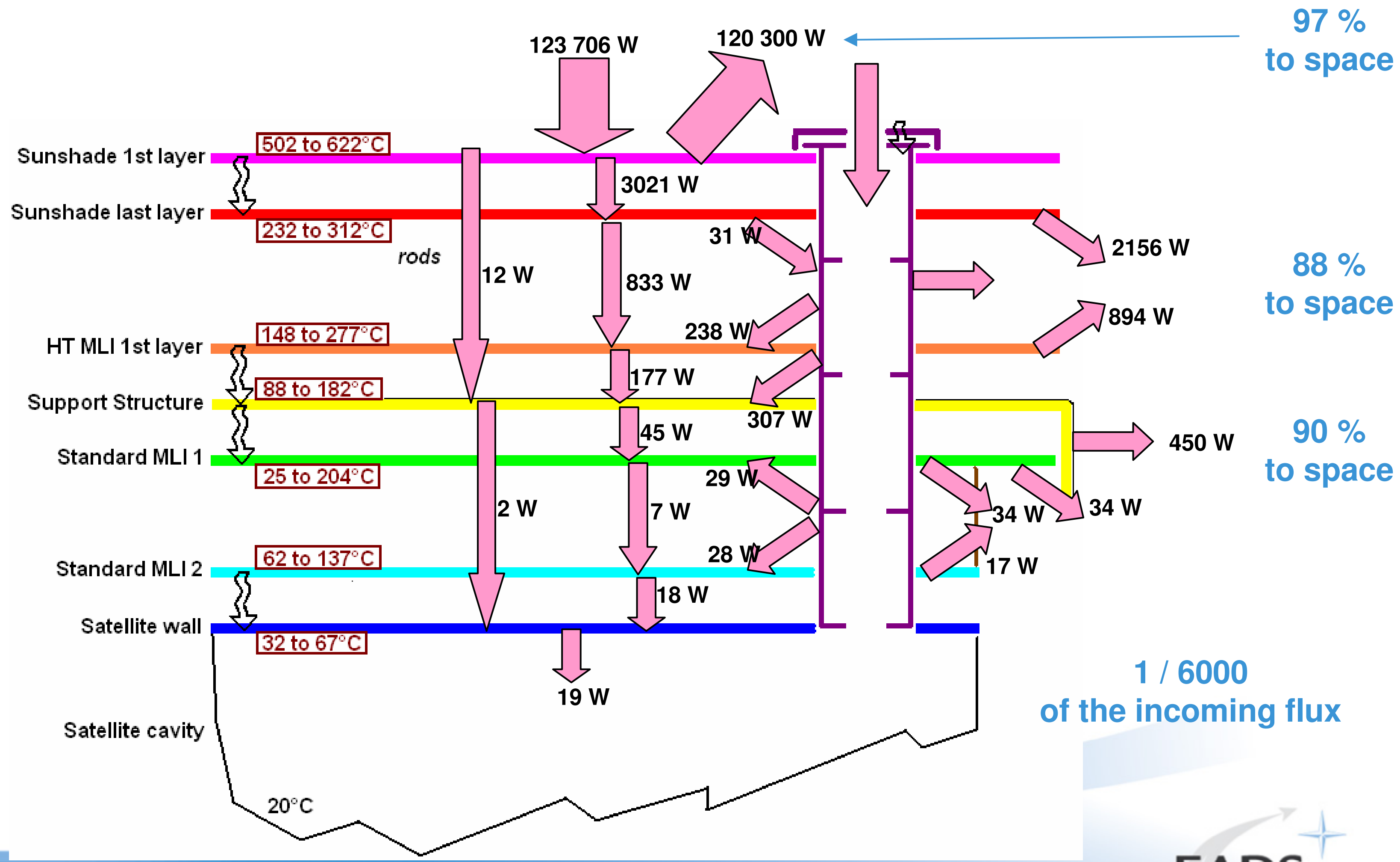
Thermal map of the one of the possible configuration Flight Heatshield thermal model (in hot case)

Temperatures meet the heat shield requirement specification

and are fully compatible with the material qualifications…

Heat Shield Flux budget

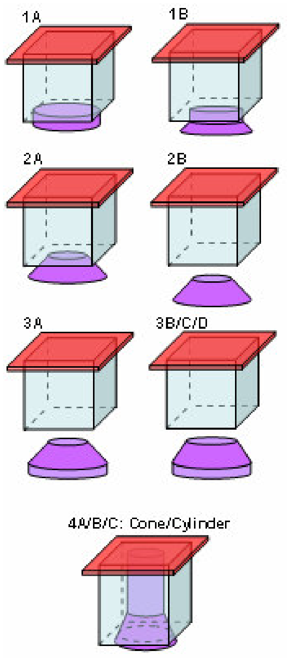
- Flux exchange inside the heat shield (after test model correlation) : Multistage
- Heat shield meets its requirement specification

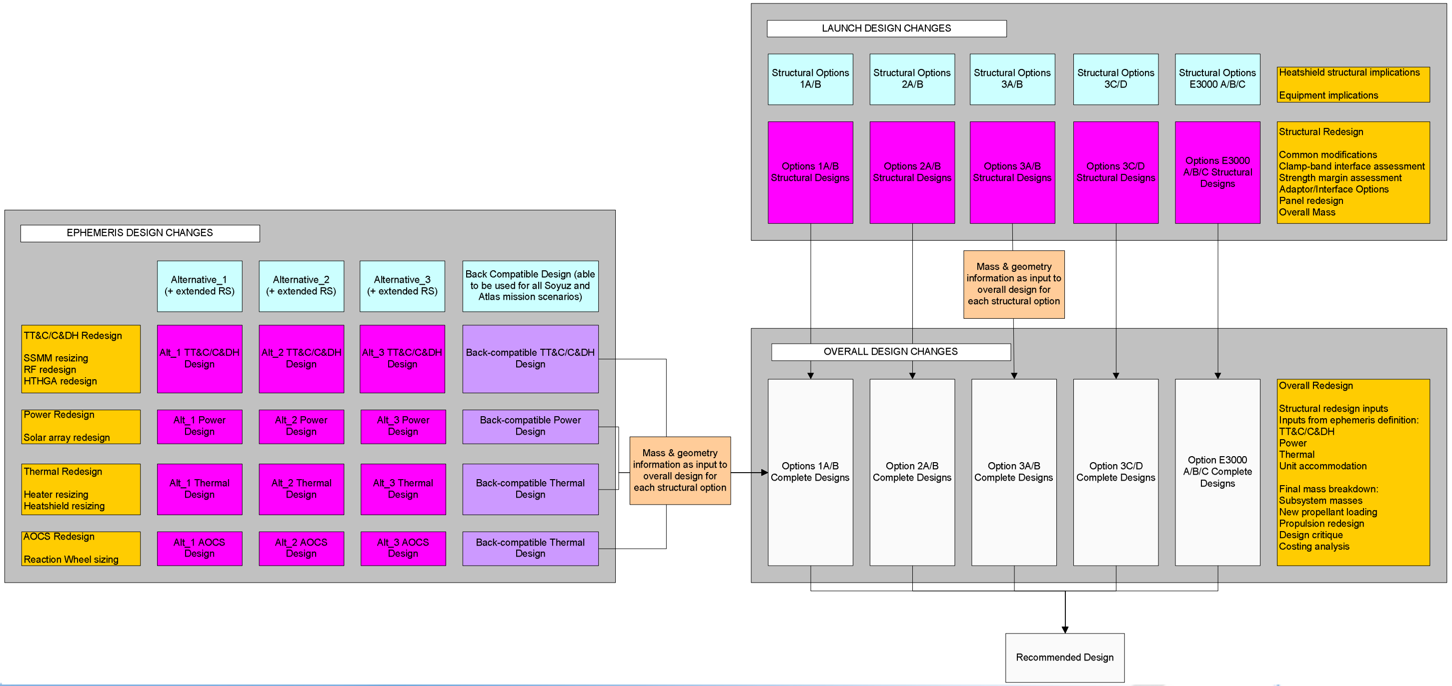


CCN1
Atlas launch

CCN1 Study Overview

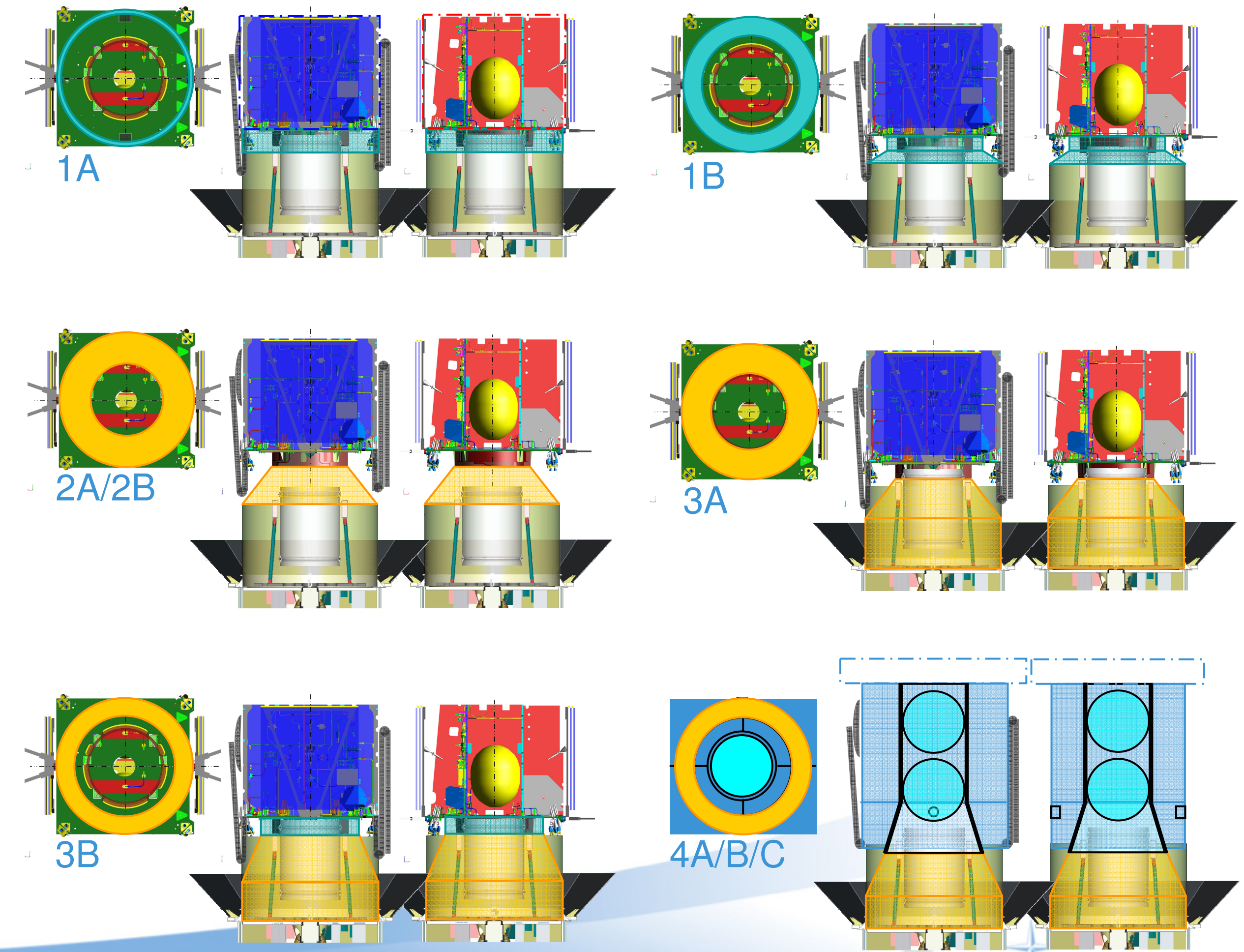
- Purpose: Analyse the design changes to the SolO mission caused by two changes to the mission baseline, namely:
  - Switching from a dedicated Soyuz-Fregat launch from Kourou, to a combined launch with the NASA Sentinels mission on the Atlas 551 launcher from Cape Canaveral
  - Extending the remote sensing schedule of the mission to enable operation of SolO in coordination with NASA's Inner Heliospheric Sentinels



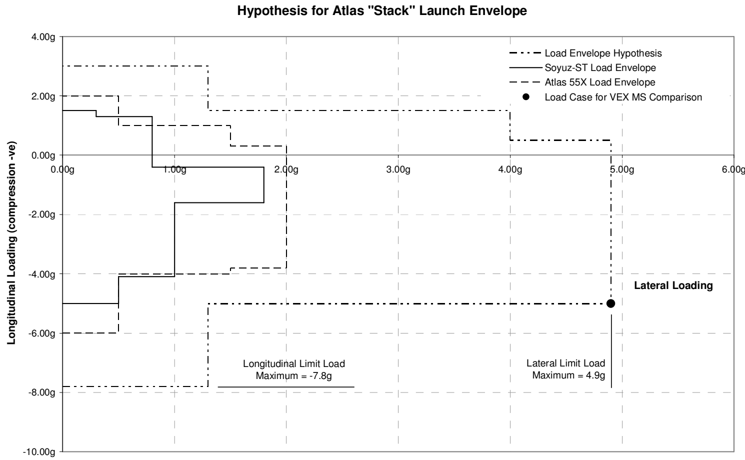


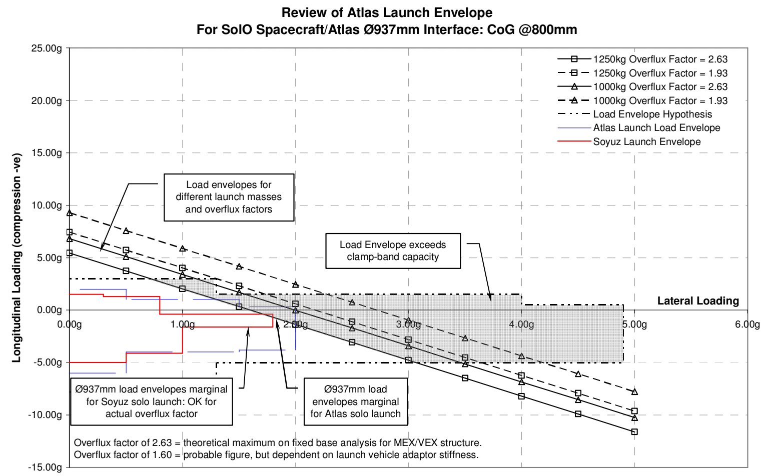
Structural Options for Trade-off

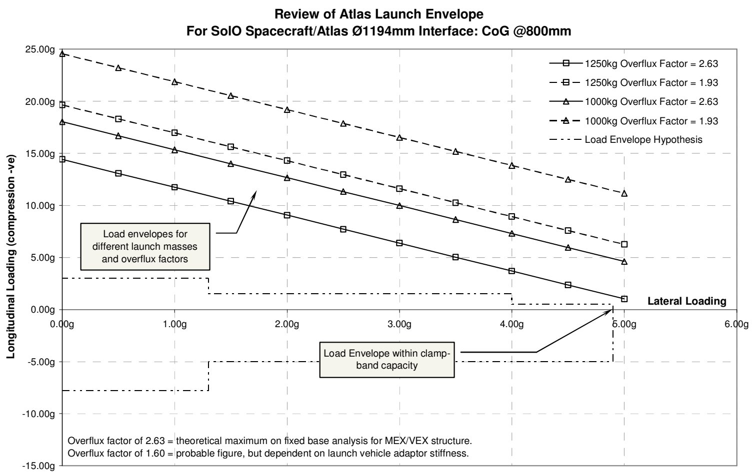
- Option 1 A: Integral Ø1666 S/C Interface
- Option 1B: Integral Ø1666 S/C Interface (Cone/Cylinder)
- Option 2A: Integral Ø937-1666 S/C Interface
- Option 2B: Jettisonable Ø937-1666 S/C Interface
- Option 3A: Separate Ø1666 to Ø937 Adaptor
- Option 3B: Separate Ø1666 to Ø1194 Adaptor
- Option 4A/B/C: E3000-Derivative Structure

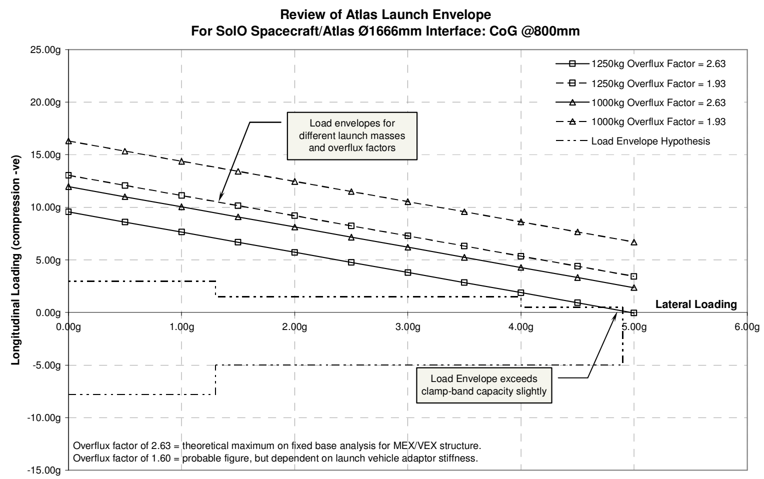


Design Changes – Launch Env.









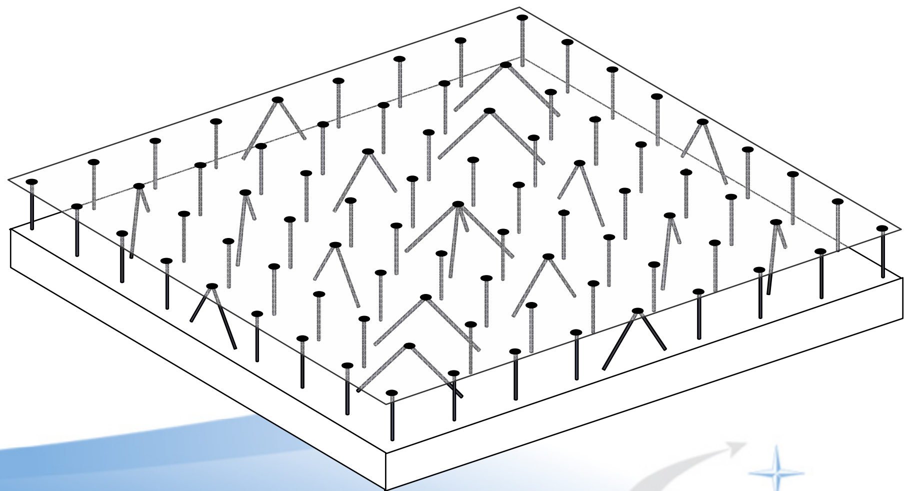
All the space you need

Design Changes - Launch Env.

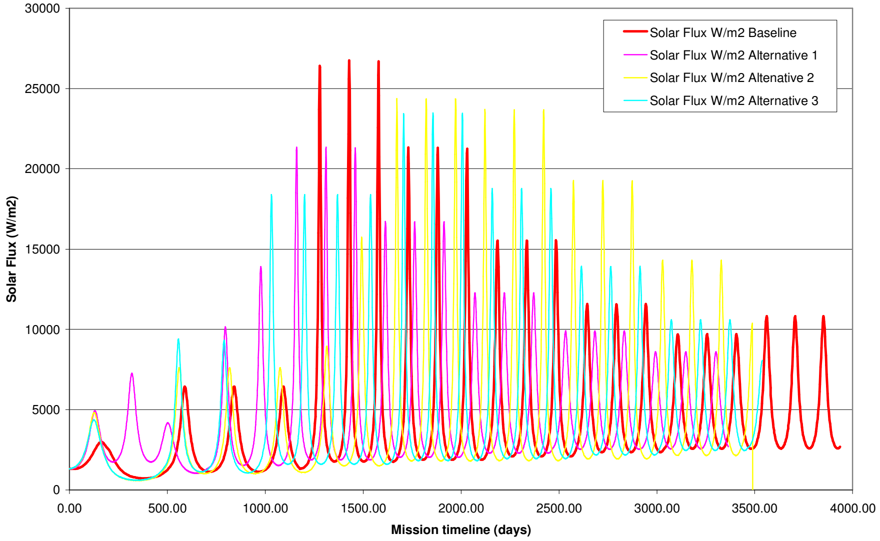
- Adaptor/Interface Options: Structure Mass
  - Analysis shows that Carbon cone-cylinder-based construction is most mass efficient
  - Cone-cylinder construction has lower clamp-band margin due to high CoG
  - Increase in mass of Contraves type structure over VEX due to reinforcement requirements in core structure

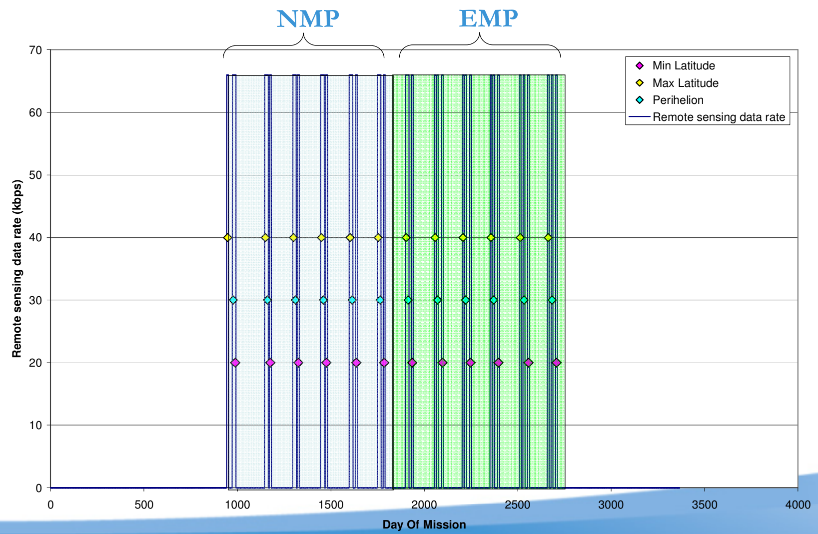
	Option	Structure mass kg	uncertainty %	Maximum structure mass kg
VEX	Contraves/MEX	133.9	2.0%	136.6
SolO (single launch)	SolO (SOYUZ)	144.0	25.0%	180.1
SolO (Atlas stack launch)	OPTION 1A	218.0	25.0%	272.5
	OPTION 1B	210.7	25.0%	263.4
	OPTION 2A	224.4	25.0%	280.6
	OPTION 2B	197.4	25.0%	246.8
	OPTION 3A	197.4	25.0%	246.8
	OPTION 3B	191.8	25.0%	239.7
	OPTION 4 A Cone/Cylinder	174.1	25.0%	217.6

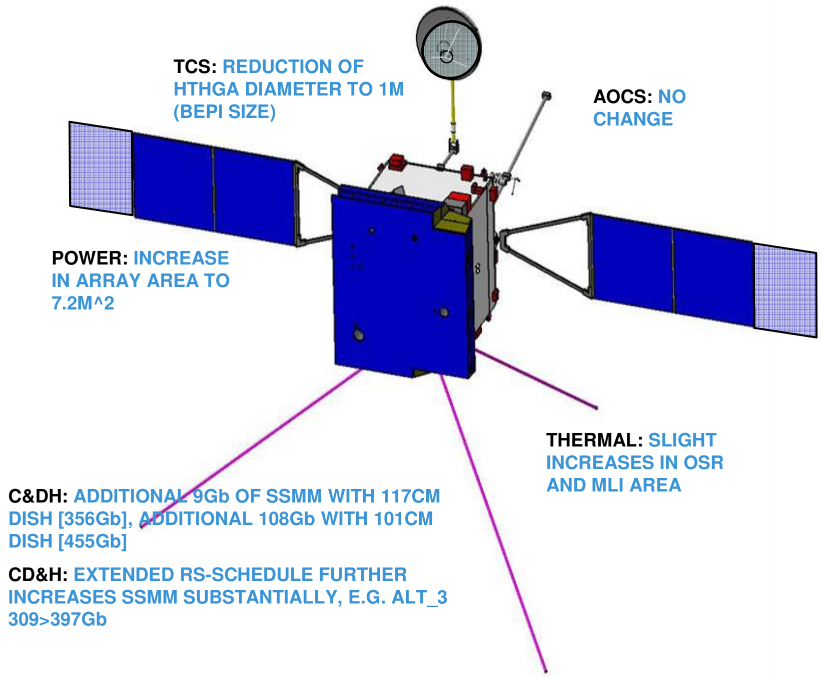
- Assessment of Heatshield Structural issues
  - Modification to pyramid, bipod and lash supported structure (right) gives margin increase to 11.0 on quasi-static load, and significantly increase first eigen-frequency



Design Changes - Ephemeris

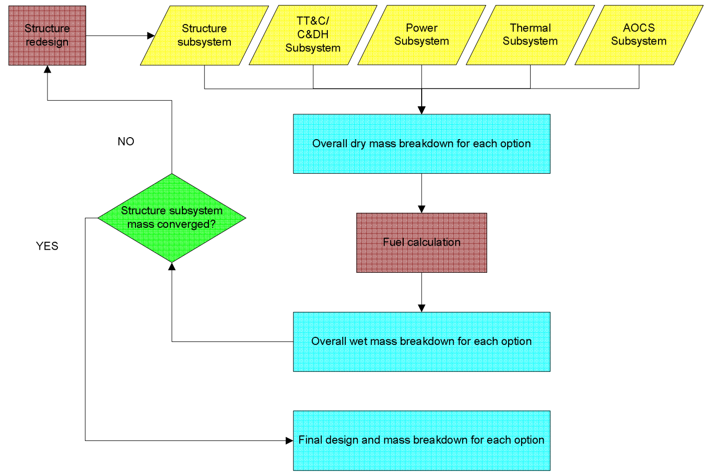


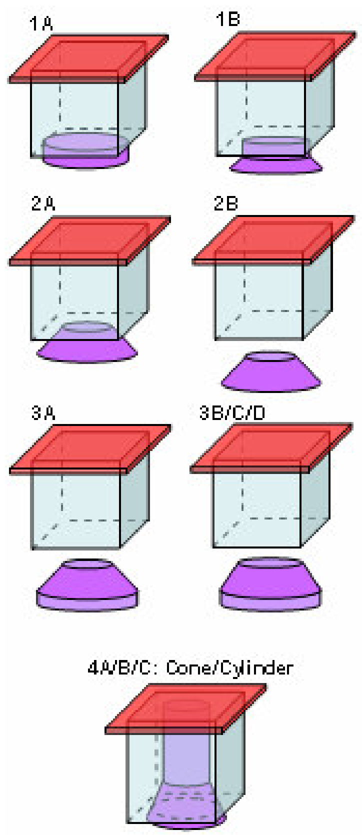


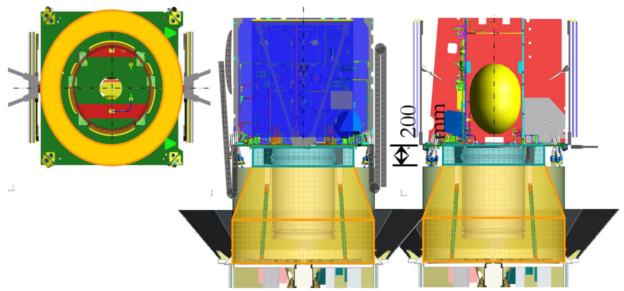


Design Changes – Overall

- Overall mass breakdowns for each option computed, for a back-compatible design



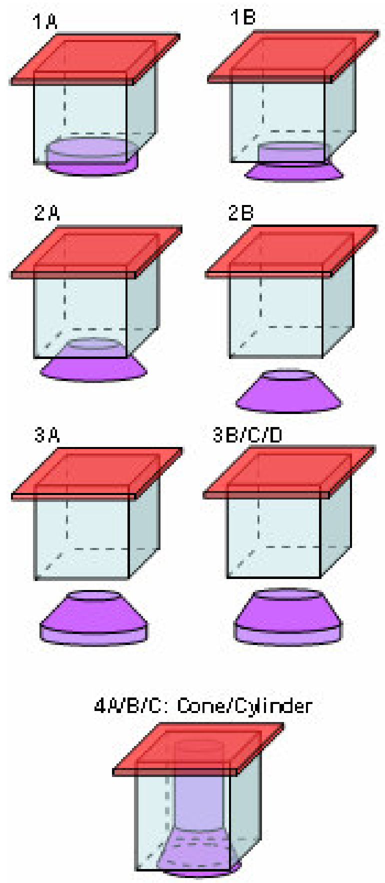




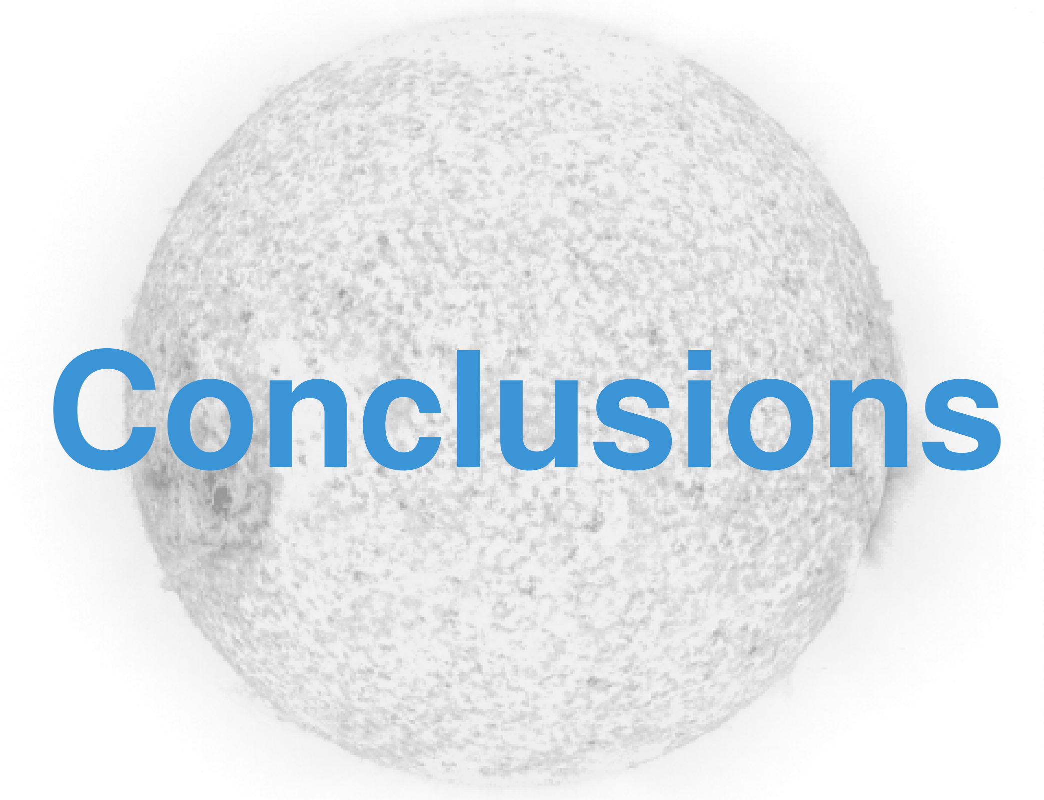
	Soyuz		Atlas		
Option	LV Margin kg	Adaptor Margin %	LV Margin kg	Adaptor Margin %	Comments
Single Launch	45.22	33.8%	100.79	11.3%	Heatshield as baseline
1A	-169.32	196.7%	-47.95	25.5%	Heatshield as baseline
1B	-142.65	151.1%	-23.31	9.2%	Heatshield 10% bigger to cover larger structure
2A	-169.28	93.5%	-47.92	-13.2%	Heatshield as baseline
2B	-63.40	27.9%	1.58	-57.8%	Heatshield as baseline
3A	-63.40	27.9%	0.40	-57.8%	Heatshield as baseline
3B	-115.83	89.5%	10.49	41.6%	Heatshield as baseline
3C	-97.11	93.9%	27.79	44.8%	AlBeMet Baffles and Heat Shield Support Structure
3D	-89.28	95.8%	35.03	46.2%	AlBeMet Baffles; Carbon-Carbon Shield Support Structure
E3000 'A'	-83.30	27.0%	40.56	1.3%	Heatshield as baseline
E3000 'B'	-64.58	30.0%	57.85	3.8%	AlBeMet Baffles and Heat Shield Support Structure
E3000 'C'	-56.74	31.3%	65.10	4.8%	AlBeMet Baffles; Carbon-Carbon Shield Support Structure

CCN1 Overall Conclusions

- Subsystem Design:
  - Significant changes to specific subsystem designs
- Instrument Design:
  - No major difficulties in instrument compatibility with an Atlas launch
- Structural Design:
  - Significant increases in structural mass
- Overall Design:
  - Options 3A/B/C are all fully compatible with the Atlas launch
- Overall Design:
  - Options E3000 A/B/C are all also compatible with the Atlas launch
- Overall Design:
  - Option E3000 A is the best option, from a mass perspective, without changing from the baseline the baffles/heat-shield materials
  - Out of the Atlas-compatible designs, the best option from a mass margin perspective is E3000C – but costly!



- As a final summarising statement concerning launch of Solar Orbiter by Atlas on top of a stack of 3 Sentinels:
  - A fully Atlas-compatible design can be reached (design 3C onwards)
  - However it does not seem to be possible to achieve a back-compatible design also usable on Soyuz within the launcher mass envelope



Conclusions

Conclusions

- Instruments inputs have been analysed
- Instrument accommodation confirmed previous assessment studies: Thermal control is the driver

- Update of Solar Orbiter System design
  - Coherent with new payloads information
  - Coherent with new Heat Shield design
  - Coherent with on-going Bepi Colombo developments
- Main critical technologies have been assessed: Solar array, High Gain Antenna

- Full trade-off for Heat Shield design
- Heat Shield definition based on well-known and robust techniques
- Breadboard test program, in the closest conditions from flight, confirmed thermal design